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A CAPACITY MODEL FOR RESEARCH BASED GOVERNMENT MANUFACTURING SYSTEMS

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To the Graduate Council:

I am submitting herewith a dissertation written by Tomcy Thomas entitled "A CAPACITY MODEL FOR RESEARCH BASED GOVERNMENT MANUFACTURING SYSTEMS." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Industrial Engineering.

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A CAPACITY MODEL FOR RESEARCH BASED GOVERNMENT MANUFACTURING SYSTEMS

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DEDICATION

To my LORD and Savior Christ Jesus for blessing me more than I could ever ask, think or imagine. To my mother who conceived me, bore me and gave birth to me. To all those people who were a positive influence in my life. To my wife Susen, who is always supportive of me especially during the difficult phases over the last few years. To all others, who gave valuable lessons in life.

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ABSTRACT

Manufacturing systems take longer than necessary to be designed and implemented, hence the greater developmental cost. A class of manufacturing systems exist which would benefit from the concepts of reverse engineering, to reduce lead times for establishing critical manufacturing capabilities essential to national safety and security. There is a need to reverse engineer these manufacturing systems as no current system and/or body of knowledge exists. Manufacturing systems vary in their ability to deliver products in an efficient and reliable manner and hence the variability in national readiness. Presently the design of manufacturing systems for some critical operations ranges from an educated trial and error process to duplicating from documentation and professional expertise. The literature search highlights the non-existence of a current systematic operational reverse engineering model that could be the standard for designing manufacturing systems.

One of the main constraints in the manufacturing is that the time for production is limited and denoted by time available (TA). The time to finish (TF) is the time needed to complete the manufacturing operations in a facility so that the entire quantity demanded is produced, from start to end, in the production line. If the TF is less than the TA there is sufficient capacity to meet the demand. Literature search indicates that no study has been conducted to compute the TF. Further, it also indicates that no study has been carried out focusing on the

impact of variations and disruptions at the design stage, even though these topics are covered in analysis of existing operational systems.

The algorithms and mathematical model were developed. The model will compute the exact TF taking into account variation, disruption and flow issues. The equation for TF was developed. The model to be designed is validated using information from a government manufacturing system.

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INTRODUCTION

1.1 Background and Motivation

There is a class of manufacturing systems that establish critical manufacturing capabilities essential to national safety and security. These manufacturing systems are small, percentage wise, when considering the total manufacturing in the US, but large in diversity and national impact. An example of how manufacturing of a particular product will affect the future innovation and national importance is the space missions [1]. There is not much work published about how government production capabilities affect national innovations, safety and security. Most products coming out of research, even from the national labs in the United States, are commercialized by private industries; the government does not control the manufacturing except for a very few products which are detrimental to public safety if not controlled (an example is nuclear materials and products). The following are environments which require significant manufacturing system design:

1. There are certain products of national interest that are not currently being manufactured in the US for a variety of reasons including procurement of the product from external sources. An example is when imported products require re-establishment of non-existent processes and skills due to political circumstances.
    a. Since these products have not been produced for some time, the necessary facilities for manufacturing do not exist.

b. In some cases, the product has not been produced in such a long time that the knowledge necessary to manufacture the product no longer exits.

2. There are new products developed through research efforts of the government that have the following requirements:

    a. Products produced in a research environment in which processes need to be scaled up for commercialization.

    b. Current products that require significant design and functional modification and therefore a redesign of the manufacturing process.

3. There are manufacturing systems that are obsolete from an operational and technological perspective that are currently in need of a major redesign.

There is no current systematic approach that allows an efficient and reliable operational manufacturing system to be designed in the least possible time, considering the environments described above. Typically, the processes are designed based on expertise and experience. Without a systematic study of the product and the mechanisms by which it is assembled, much effort will have to be expended to understand how to manufacture this product. This trial and error approach has its associated cost; hence valuable resources may have to be wasted for this process. In addition, the length of time required to complete the production process design is excessive. As a result, the effects of trial and error approach are the following: (1) products in the environments discussed will take longer than necessary, (2) there is considerable variation in the efficiency and reliability of those systems, (3) there is greater cost in developing that manufacturing process, and (4) the ability of the industry to introduce products to market will be delayed. This research is focused on creating a standardized approach to design operational manufacturing systems. The methodology developed in this dissertation could be used from a single user perspective as focusing on the scalability of research-based production to manufacture the demanded quantity. It could also be used as a production planning tool so that the planners will have an exact idea as to how the activities are to be arranged on the production floor in advance. This dissertation focuses on the perspective of the user to design their manufacturing operations.

1.2 Problem Statement

There is significant variation in manufacturing system design with the key variability resulting from the history surrounding the manufacturing process, personnel available and their level of expertise. The design of manufacturing systems critical to the national interest ranges from an educated trial and error process to duplicating the process from documentation and professional expertise. The literature search, presented in Chapter 2, highlights the non-existence of a current systematic operational manufacturing design model that could be the genesis of any level of standardization. This lack of standardization impacts national readiness. Manufacturing systems take longer than necessary to be designed and implemented and hence the greater developmental cost. Manufacturing systems vary in their ability to deliver products in an efficient and reliable manner and therefore impact national readiness.

The focus of this research is to create a conceptual framework and the supporting rationale and methodology that allows for one to design an operational manufacturing system based on the concepts of operational excellence. The specific objective of this research topic is to design a manufacturing system for a product whose manufacturing processes are ill-defined and whose production line is non-existent. Any operational excellence framework must, beyond the fundamentals of the physical equipment, consider flow, disruptions and variation in the system [2]. These three principles each have a unique focus and approach but are not independent of each other. Therefore, the key objectives of this research are:

1) Create a conceptual framework that integrates the concepts of operational excellence into the manufacturing design framework.
    a. Study the flow issues.
    b. Study the effects of variation.
    c. Study the effects of disruptions.
2) Study the effect of those issues on the operational time (CT and TF - details in Section 1.3).
3) Reduce time and cost in designing production processes.

A suitable manufacturing/production system should be designed and developed to manufacture a given quantity per year (demand - example 2000 units/year) of a product. **<u>The demand should be met in full and hence the throughput of the system should be at least equal to the demand</u>**. There are many units (manufacturers) involved in the manufacturing chain for the product from its initial materials to the final product. Each manufacturer in the chain has constraints and limitations. There are many system level constraints to be satisfied for the production to be successful. Available facilities are to be retrofitted for this product with explicit production requirements. Some of the manufacturers' internal systems do not allow for changes, whereas some are open to be redesigned completely and others are only open to some changes.

Instead of using trial and error approaches to design the manufacturing system, this proposed research approach provides a design which will eliminate the wastage of resources during the design phase. The literature review indicates that no work has been done applying operational excellence during the design stage of a manufacturing system. The approach to apply operational excellence to create a standardized design of a manufacturing system is outlined in the general approach in Section 1.5. The negative impact of variability is to be overcome by having the ability to withstand increased variation and by establishing a system where output from each manufacturer conforms to the standards of the design.

1.3 Research Context

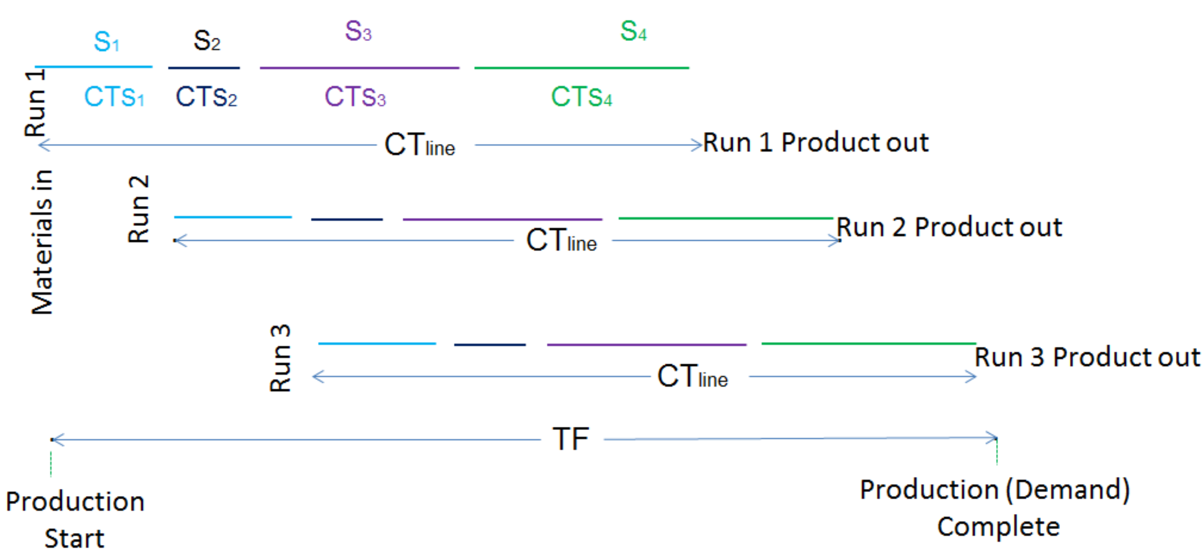
One of the main constraints in manufacturing is that the time for production is limited. The following defines/explains the terms related to time, used in this research work. The average time a job takes at a station is the machine/station cycle time

($CT_{station}$). The average time from the start of a job at the beginning of the line until it comes out at the end of the routing (when there is more than one station in the line) is the cycle time of a given line/routing (CT_{line}). The lead time (LT) of a given routing or line is the time allotted for the production of a part on that routing or line is. Cycle times are generally random whereas the LT is a constant [3]. The CT vs LT combination looks only at the fact of whether or not a unit or batch of product or part meets the customer requirement given that LT is developed based on TAKT time.

Capacity is checked in a new way in this dissertation. In industry the production capacity is defined as the maximum quantity of products that can be produced in a unit of time in the optimal operating conditions [4]. Capacity determination from various sources in literature is given in Section 2.1. The literature does not discuss the actual time to produce/manufacture the quantity set as the capacity or demand. In this dissertation research, a new term, time to finish (TF) is introduced. The TF is the time from start to end in the production line until the entire quantity demanded is completed; it is the actual manufacturing time to finish manufacturing activities for the entire demanded quantity. The term time available (TA) is used to represent the duration for which the facility is specifically allocated for the manufacturing of this product only. **If the TF< TA, then there is sufficient capacity to meet the demand.** This TA could be in one time block or in different periods (time blocks). The TF vs TA combination denotes whether the entire quantity demanded can be delivered within the constraints. The manufacturing operations are to be finished within the allocated time and hence unfinished work is not an option.

The computation of TF will help in determining whether the suggested operations are practically feasible.

CT and TF are not the same, even when the TA is in one single continuous block. The reason being that CT focuses on the completion time of each unit whereas TF focuses on the completion time of the whole demand. An example is shown in Figure 1.1 assuming that there are three production runs needed to complete the demanded quantity. The time taken for each production run is the CT_{line} for that run. The TF is the actual time from the start of the production until the demand is completed. If there is only one production run required to meet the demand during the time frame allocated, then, the CT_{line} and the TF will be the same.



This repeats for every period (p) if the time is allocated in different periods rather than a single continuous period of time allocation. If this is the case, $TF = TF_1 + TF_2 + ... + TF_p$

Figure 1.1 CT and TF are different

If the TA is spread across different periods (p) it is denoted as TA1, TA2, ---- TAp and the corresponding time to finish are denoted by TF1, TF2, ---- TFp. TF is applicable when the time allocated is in one block whereas TF1, TF2, ---- TFp is applicable when the facility is allocated for different periods in a calendar year. An example with the time allocated in a single continuous period and the situation where the time is allocated in three different periods (TA1 to TA3) is shown in Figure 1.2. The value of TF (TF1, TF2… TFp if time is allocated in different periods) are to be computed. The time left over in any period cannot be used in any other period, but it can be used to produce more units if needed. If the total demand is to be met through manufacturing operations in different periods, the total demand will be divided into sub-demands corresponding to the time for each period allocated. The TF for each period is computed with respect to the TA for that period. If much time is left between the TFp and the TAp, then the demand for that period will be increased and the TFp will be recomputed. This will guard against the time not being properly utilized, and it will cover for some other periods later.

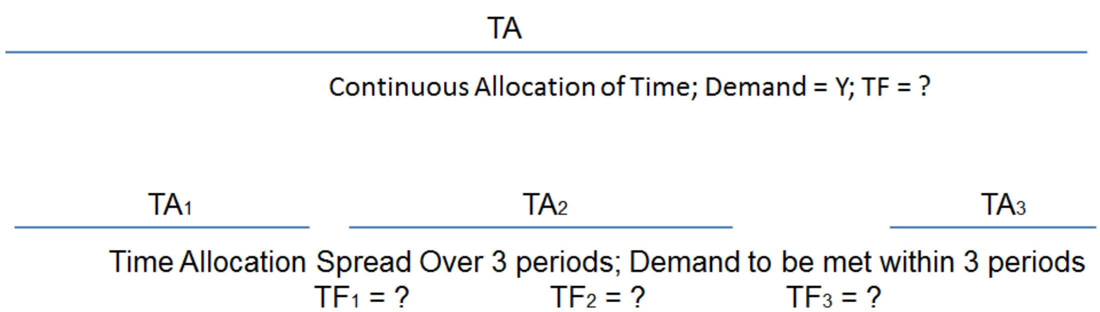


Figure 1.2 TA Continuous versus TA in Multiple Periods

Manufacturing spread across different periods will have more variation compared to the production processes occurring in one single block. The reason for this is because the startup operations are to be carried out at the beginning of each period, resulting in a considerable amount of time spent for activities which are not productive but needed. The shutdown activities are to be carried out at the end of each period. In the TF approach there are more startups, setups, and cleanup activities if the manufacturing is spread over different periods compared to one single continuous allocation of time. Shutdowns are more specific because material cannot be left in the manufacturing facility. Also, the set up and cleanup activities of every station is to be repeated in every period. As a result, the time required to manufacture the same quantity of products will be much more when the time allocated is spread over different periods, rather than one continuous single period. In contrast, manufacturing carried out in one single continuous period of time will have only one start up and shut down activity.

TF will be computed for all cases and checked with the TA. If the actual operating time (TAO) is less than the TA, then the TF will have to be compared with TAO (TF < TAO). In factory environments, there are laws with respect to the break time which may force the TAO to be less than TA, which is discussed in Section 3.3.

1.4 Boundaries, Scope and Limitations

1.4.1 Product and Customer Characterization

- The product is in demand for government programs such as space research and is highly sensitive and regulated. It is to be produced exclusively for the government agency (customer).
- A steady and stable supply of this product is required for the foreseeable future. The customer demand is based on delivering a specific quantity of this product annually.

1.4.2 Supply Chain Infrastructure Characterization

- The supply chain of this product spans many organizations which are widespread location-wise. It consists of the supplier of the main raw material, the manufacturers and the consumer of the product who will deliver it to the customer for their use.
- The manufacturing activities reside over multiple facilities. Turnkey production facilities do not exist for the whole manufacturing chain.

1.4.3 Facility Infrastructure Characterization

- Manufacturing facility (physical infrastructure) exists. These facilities were built for some other purposes and are now being used for the manufacturing of this product.
- The physical facilities of at least one manufacturer cannot be changed or modified; machines cannot be added.

- All the transformation processes for a particular manufacturer in the chain have to be finished within a restricted number of days as the facility is not available year-round. Special setups can be carried out before the actual start of the manufacturing process. The manufacturing facilities are capable of operating 24/7.

1.4.4 Manufacturing Infrastructure Characterization

- The focus of this dissertation is on the manufacturing section of the supply chain. The manufacturing processes are in discrete batches. The manufacturing is sequential in nature; a workstation processes the output of the previous workstation. The output product from the initial manufacturer in the chain is the main input material for the next manufacturer.
- Since the system is imbalanced, it may not be possible to have the same capacity in all process areas of a particular manufacturer. The reasons include but are not limited to: (a) cost, (b) technological challenges and (c) regulations.
- The facilities of a particular manufacturer involved in this transformation chain are dedicated to several products critical to national interest. However, dedicated time is given to each product during the year in which only that particular product is manufactured. The dissertation focuses on a single product. The production facility of this particular manufacturer is allocated for this product on a continual basis for the duration allowed. The

other products are manufactured in this facility using the remaining time (manufacturing of products has to occur because of long term contractual obligations).

- Demand is to be met within a specified time period for a manufacturer because of the above-mentioned limitation.
- Process time is much longer (weeks) for the last two manufacturers in the chain. The transportation time between process areas of a manufacturer is negligible (close to zero) compared to the actual processing time (It will be pulled in when needed).

1.4.5 Additional Scope

- The required time to finish (TF) the production quantity, as given by the demand, is much more important than the time required completing each unit of the product, in the case of the manufacturer(s) whose facility is time restricted for this product.
- Once the demand is met, the production may not continue for that year even though the facilities are still available in that year as per the early allocation.
- The key measures are TF and TH (TH is set equal to demand which is known), the number of production runs (X_3) and the number of batches (X_2) in each production run. As the focus is on TF, the CT is not one of the key measures.

- There cannot be any inventory buildup in between the process areas in the case of a manufacturer. The transformed material stays in the machines until it is sent to the next process area.
- At the end of the manufacturing process for the period, there should not be any material remaining in the process areas (stations) of $Mfgr._n$. If the TA is spread across p periods, the WIP_{end} of each period is to be zero.
- The dissertation will look into the aspect of operations in ideal conditions, as well as practical conditions.

1.4.6 Assumptions and Study Limitation

- All the materials are available at the time it is scheduled.
- The facility layout is available and completed. Design of the physical infrastructure is out of scope for this study.
- This manufacturing system has limitations based on existing facility and equipment for some of the processes in the production. Therefore, initial infrastructure is assumed to be available.
- Raw material procurement (for the transformation process for the manufacturing) and transportation to the manufacturer is out of scope for this dissertation. The final product is stored in a storage facility and the customer will pull the required quantity when needed. Customer will make arrangements for the transportation of the final product. The shipment of the final product to the customer is also out of scope of this study.

1.5 General Approach

The various factors of the manufacturing process are to be designed from a systems perspective. Systems are composed of elements, functions and interconnections [2]. The elements and functions are already defined in Section 1.4. The various elements are product, customer, facilities, supply chain and manufacturing. The function is a given quantity of the specific product in a given period of time and the manufacturing cycle continues in the next period. The interconnections are defined through TF, number of production runs and number of batches in each production run in ideal conditions and practical conditions where flow, variations and disruptions are taken into account. The manufacturing system studies the interconnections from a throughput (TH) perspective (which is defined by TF compared to TA). The focus is on getting the manufacturing done with less TF, which in turn will depend on the CT, number of production runs and the number of batches in each run.

An algorithm is developed based on the key areas of operational excellence such as flow, variation and disruption [2]. The output of the algorithm is the different options for the operational manufacturing system design. In practice as seen in industry, systems are designed/developed initially and then improved using various continuous improvement tools to mitigate the effects of flow problems, variations and disruptions. This dissertation takes into consideration the effects of flow, variations and disruptions in the system design itself.

Normally manufacturing is viewed in a forward direction of converting materials into output by suitable manufacturing processes using other resources. The materials from the supplier(s) are converted to the product using suitable manufacturing/production techniques before it is sent out to the customer. This particular approach looks in the reverse direction starting from the product features and customer demand, and then finds the proper mechanism to meet the demand taking into consideration the constraints in which the system should function.

1.5.1 Base of logic

One important performance measure of any manufacturing system is the throughput (TH). "The average output of a production process per unit time is defined as the system's TH. It is the average quantity of good (non-defective) parts/products produced per unit time [3]." According to Little's Law [5], TH is dependent on CT and Work-In-Process (WIP); when the system operates under steady state. The important factors which affect the CT are flow, variability and disruptions [2]; when CT changes, TH and WIP also change. These factors also have an impact on TF. Figure 1.3 shows the connection between them and also the various factors affecting them. The important parameter in this research is time; hence the application/comparison of Little's Law is valid. Since the focus of this dissertation is on the time factor, the structure in Figure 1.3 does not focus on WIP.

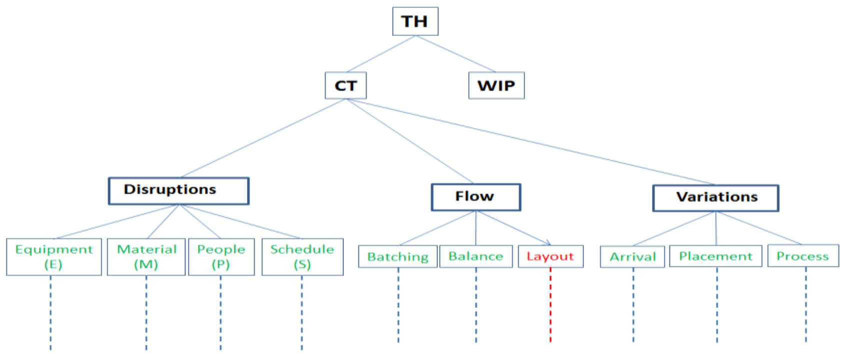


Figure 1.3 OE factors tree structure

Variations could happen anywhere in the system; this dissertation focuses on the variation in the arrival, processes and placement. Any manufacturing system is composed of four critical resources (CRs): (1) Materials (M), (2) Equipment/Machines (E), (3) Personnel (P) and (4) Schedules/Information (S) [6]. Disruptions to any of the four critical resources will affect the time (TF and CT). The TF is determined or affected by the number of production runs, number of batches in each run, quantity in each run, the $CT_{station}$, variations, disruptions, processing time at each station and the wait times.

There are three types of wait times in any manufacturing operation: (1) wait time of the queue denoted as CT_q, (2) transfer wait time if a station has to wait for a particular number of batches to be processed in the previous station and (3) additional wait time (denoted as WT_{factor} in the computations) because of the availability of subsequent stations. All three types of wait times increase TF. The additional wait time (WT_{factor}) is because of blocking and is very significant in operations where the inventory buffer between stations is restricted or even set to zero. When the stations get blocked more, the TF increases which reduces the capacity to meet demand. Layout changes are not considered in this dissertation and hence flow design concentrates only on batching and balance.

In the proposed methodology, the design includes the concepts of operational excellence involving flow, variations and disruptions. This dissertation assumes that the machines are available, and the physical infrastructure is in place. Concepts of lean/smart manufacturing and Toyota Production System (TPS) [7] helps in designing a manufacturing system which includes the concepts of Operational Excellence (OE) in the development stage itself, with a reduced TF and CT.

In the mathematical computation for TF in Section 3.2, first, the impact of variations and disruptions are considered separately, and then, a single equation is developed which captures the effect of both issues together. The flow is incorporated in the equations by the number of production runs and the number of batches per run. The design starts with the concept of ideal conditions. An ideal condition is where there are no disruptions or variations anywhere in the system. When the variation increases, the CT and hence the TF, increases which results in the TH getting reduced. When variation increases, the processing time goes up. Simulation was used to study the effect of increasing processing time as a result of variation. See Figure 1.4 as an illustration of variation on TH and CT on a system not designed to withstand variation. The same system with the process time kept at the base level, if disrupted for any reason, results in TH going down further and CT goes up as shown in Figure 1.5. Variation affects the processing time of any station or system. Knowing

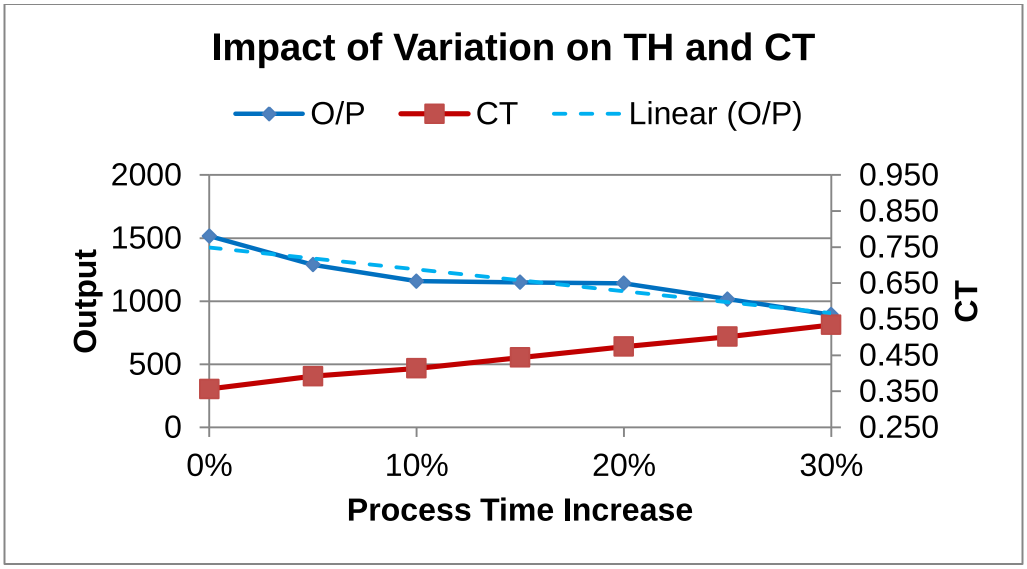


Figure 1.4 Variation affects CT and TH

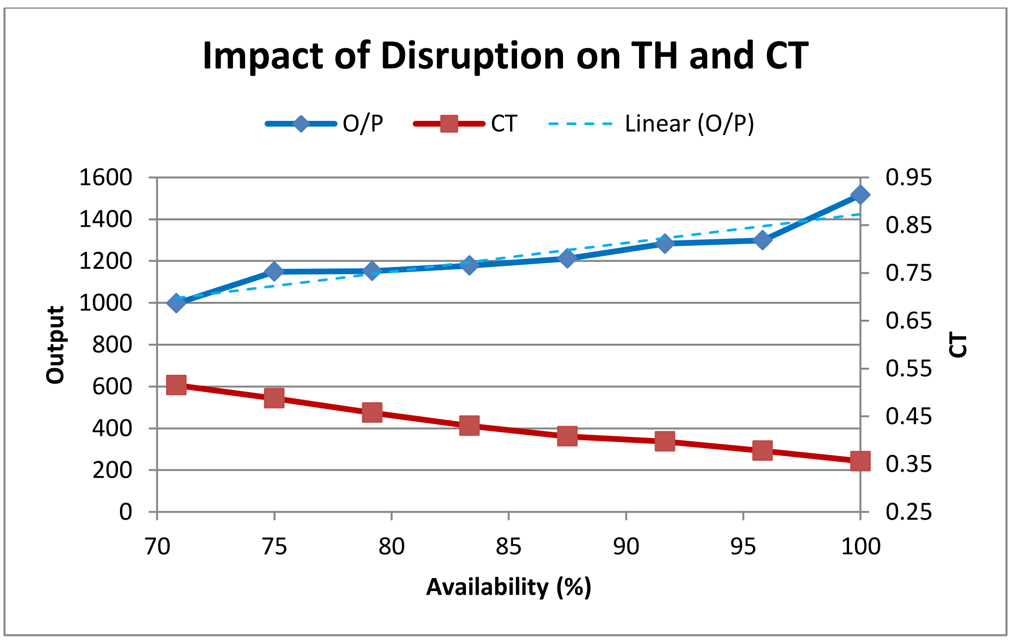


Figure 1.5 Disruption affects CT and TH

that as a fact, a study was conducted directly to see the impact of process time increase on TH, CT and TF. The result of which is shown in Figure 1.6 for a system not designed to withstand variation. There is a point beyond which the processes cannot continue if the TF is constrained to be below a particular value.

1.5.2 Tools Used

An algorithm was developed to compute the TF to successfully manufacture the product. The algorithm was implemented in MATLAB to get the results. The developed algorithm created the rule based, model driven program to design the operational manufacturing system. A mathematical model was developed based on the Factory Physics [3] equations. For the validation of the model, a simulation model, developed and verified by the subject matter experts for the associated case study, was used. Simulation over forecasts or under forecasts results; in most cases, for the software used in the study, it over forecasts the results. To overcome the problems of over or under forecasting, the model was run multiple times before selecting the final version. The algorithm was tested, and the model results were compared with the simulation results so that the results match to the extent possible.

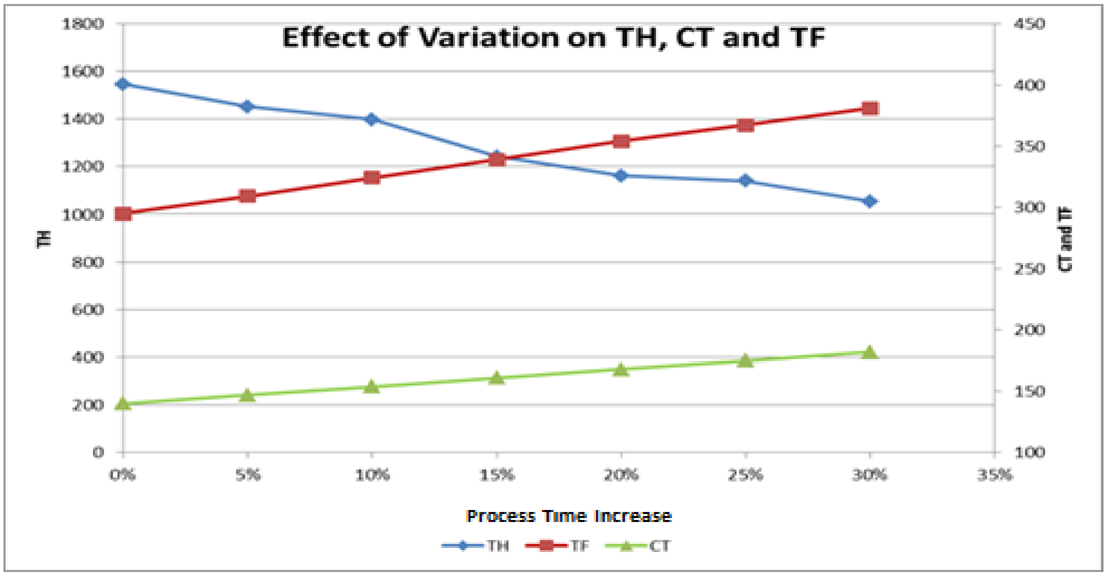


Figure 1.6 Process Time Increase and its effect on CT, TH and TF

1.6 Conceptual Framework

To efficiently put together a good production system, the concepts of lean design, reliable process design, controlling variations and looking at the constraints from the theory of constraints perspective are needed. The production process will have to be designed not only by looking at the capacity of the equipment, but also the product flow, the logistics of how the parts are brought in, the schedule and how the processes are managed. The motivation in Section 1.1, the problem statement given in Section 1.2 and the scope and limitations in Section 1.4, defined the need and purpose of this research and the boundaries within which the research is bound respectively. The general approach in Section 1.5 explained why a more robust and holistic operation excellence model is needed in the design stage itself. The framework/methodology is based on the following rationale which is explained in more detail in Chapter 3.

A. Model Design Inputs

1) Product and Product Characteristics

Define the product and its fundamental framework for manufacturing. For each manufacturer, the product characteristics and details, along with the bill of materials, dictate the manufacturing processes. The manufacturing process is known. The demand is the leading factor for the capacity analysis. A key data point is to see if the equivalent of a Bill of Material (BOM) exists that could provide an insight into the fundamental manufacturing operations that need to be supported.

2) Technology Options

A review of manufacturing technology is investigated to understand the capabilities and capacity of each alternative. These options are stored in a database. The feasible solutions are determined based on the ability to meet current and projected demand.

B. Capacity Determination

1) Design Based on Ideal Conditions

Ideal conditions occur only when there are no variations or disruptions in the system and are found only in perfect systems. The capacity of the system will be tested to see whether the demanded quantity can be produced. If it cannot be produced in ideal conditions, then there may be a need to build additional facilities. This dissertation assumes that the existing facility can meet the demand in ideal conditions; in addition, facilities cannot be changed or added for some manufacturers.

2) Design Based on Practical Conditions

Here the design considers the issues related to Flow, Variations and Disruptions and design the system to produce the required quantity demand (**set TH = demand**). It is to be tested to see whether the practical capacity meets or exceeds the demand. If it cannot be met, then the existing facilities may not be enough for the manufacturing of the product; capacity improvement by adding more physical infrastructure may be needed.

The actual operational aspect of the negative effect of variation and disruption is that the time required to complete the whole process increases as the variation and disruption increases. Since the processes cannot be completed in the same time, with variations and/or disruptions, compared to ideal conditions, the throughput reduces within the time period considered. The TF and the CT increase as a result of increasing variability or disruptions.

C. Design Changes

1) Evaluation of Design Options Based on Flow Efficiency

Flow is studied and determined; the TF is estimated. If there are problems associated with flow, the CT may increase, thereby affecting the TF and TH. A different set of options is evaluated to ensure that it adheres to the lean concepts. The basic fundamental principle is to ensure maximum throughput of the process by making sure that the principle of balanced lines with minimum lot/batch sizes are assured. Pull systems are considered as an option to balanced single piece flow.

2) Evaluation of Design Options Based on System Variations

Effects of variability are studied next; the revised TF is estimated. When variability increases, the CT and WIP increases and the TH goes down if the system is not properly designed to withstand the effects of variation. TF will also be increased if variability increases. The feasible options from the previous step are evaluated to examine several different aspects of variation. The first dimension of variation is straight forward to understand the impact that it would have on the product quality. This obviously depends on the decisions made in the flow design as variation has a greater impact on CT in push systems as compared to pull systems.

3) Evaluation of Design Options Based on System Disruptions

Disruptions tend to slow down the manufacturing processes by increasing the CT. The TF is recomputed based on the impact of disruptions. The feasibility options from the previous step are evaluated to examine two key disruptions; setups and maintenance. Each of these two disruptions is evaluated based on frequency of failures and the length of failures. Following the principles of disruptions in production processes, it is best to avoid frequent failures and long lasting failures.

Initially, the design looks into the aspects of a perfect system or ideal conditions. A perfect system has perfect flow, perfect balance and a single piece flow or a small batch size close to a single piece system; it also requires perfect material at the right time [2]. Balance can be achieved by: (1) Schedule, (2) People, (3) Shifts, (4) Tools and (5) Equipment [2]. A perfect system does not have any variation or disruptions and has full employee engagement. Once the design meets the demand with a near perfect system concept, the effect of detractors will be added to the design. There cannot be perfect balance; the focus is to achieve the best balance possible.

1.7 Contributions

1.7.1 Impact of the Model for the Government

1. Reduction of the time to design operational manufacturing systems
2. Reduction of the cost of designing operational manufacturing system by avoiding more trial and error methods
3. Improvement of system effectiveness

1.7.2 Theoretical and Methodological Contributions

1. A conceptual framework and methodology to design operational manufacturing systems is developed.
2. The modification of Little's law using TF instead of CT is presented.
3. The logic provided in this dissertation does not exist in literature and the gap is identified in Chapter 2.

4. A new logic to check the balance of the line and to identify the cause of imbalance, using Mean Absolute Error Cycle Time Overall (MAECTo) and the Coefficient of Variation Overall (CVo) (Section 3.5) has been presented.
5. A rule based or model driven (not data driven) algorithm has been developed on this concept/logic, which allows users to customize their design.
6. The quantitative model developed to compute the TF. A mathematical relationship between the TF and its variables is developed.
7. The developed equations give an accurate estimate about the time needed to manufacture the product to meet the demand.
8. The developed algorithms take into account the effects of detractors (flow issues, variations and disruptions) at the design stage itself so that the system will be able to withstand the negative impact of the detractors.
9. By verifying that the TF is less than TA, the production quantity is guaranteed to meet the demand. The presented algorithms eliminate the need for iterative development.
10. The model has been validated in a government manufacturing environment for which this model is developed.

1.8 Outline

The literature review given in Chapter 2 establishes that there is gap in the research done by others and the research detailed in this dissertation. Section 2.6

explains how variations, disruptions and flow issues affect the actual process time. A detailed approach and methodology by which decisions are to be made for the successful manufacturing design of the product in the required quantity is given in Chapter 3. It gives insight about the resources needed for the successful manufacturing of the product. This design starts from the customer side and works backward to the supplier side. The proposed approach is explained in Sections 3.1 to 3.9. The development of the mathematical model for TF is in Section 3.2. There are six phases in the methodology. Phase 1 relates capacity and demand based on TF and shows the modification to Little's law by using TF as a method to check capacity instead of throughput. In phase 2, the strategy to enhance capacity based on TF is defined. This phase also establishes the time buffer and the threshold. It classifies the system and also identifies the bottleneck (floating bottlenecks if more than one) and utilization. Phases 3, 4, and 5 discuss variation, disruption and flow issues respectively. Output of the model is in phase 6. In Chapter 4, all the algorithms are presented. The validation of the model with a case study and the results are presented in Chapter 5. Conclusions, recommendations and future work are given in Chapter 6.

2
LITERATURE REVIEW

A literature review was performed based on the combination of different key words, such as capacity, capacity determination, scaling up production, operational excellence, manufacturing system design (MSD), cycle time, variations, disruptions, lean, lean manufacturing, reverse manufacturing, and reverse or re-engineering or reverse MSD. The following gives key findings from the most important current studies.

2.1 Capacity Determination

There are many books and articles in literature about estimating or determining the capacity of facility/plants at the design stage itself or determining or analyzing the production capacity of existing plants. Some of those are shown below. However, none of the books or articles estimates the capacity in practical conditions without doing a continuous improvement project, which may be costly. This dissertation plans to introduce the practical conditions in the design stage itself. The production capacity is not achieved when the demand falls and also depends on whether or not the product is a made to stock item. The following are the key findings from the literature about this topic.

The maximum quantity of products which are of the appropriate quality and assortment that can be produced by an enterprise in a unit of time with the full use of the basic production assets in the optimal operating conditions is its production capacity [4]. A bi-objective optimization problem was solved by developing a robust production capacity planning model with two layers. The layers were connected to the objectives which were: (1) to find the maximum WIP fluctuation under a given vehicle quantity and (2) to determine the vehicle quantities to minimize the WIP fluctuation, as well as the probability of the average WIP exceeding the upper bound. The method for this model was based on the monotonicity of the objective functions [8]. An improvement plan in an existing automotive plant increased the production capacity by accelerating the cycle time target [9]. For a single specific machine that can produce multiple products in make-to-order manufacturing plants, a simple deterministic model to determine the capacity and its level of utilization was developed. Processing time, set-up time, product defective rate, and maintenance downtime were the variables integrated in the model [10]. A model that predicts throughput and material flow requirements with a focus on designing flexible capacity under different scenarios was developed by analyzing the capacity of the plant [11].

An important decision regarding the selection of the optimal quantity and portfolio of product-dedicated and flexible capacities are to be made by firms when planning for a new manufacturing system that can produce several products over a planning horizon. The unfavorable effects of demand uncertainties may be alleviated by flexible systems; however, compared to dedicated systems, they require higher investment costs. Numerical studies were performed to provide insights on how these decisions are affected by the factors, such as the investment costs, product revenues, demand forecast scenarios and volatilities over the planning period. The optimal capacity selection problem was formulated for this study [12]. To explore optimal internal pricing and capacity planning, for a service facility with finite buffer capacity, an economic model was developed. The jobs that arrive when the system is full, will be rejected because of the limited buffer capacity. The system administrator was given two separate prices for accepted and rejected users at any desired demand level by setting a sufficient condition. This desired demand level becomes the unique equilibrium of the system. For the marginal capacity pricing to be optimal, another necessary and sufficient condition was set [13]. Many basic system design decisions, such as selecting a manufacturing technology for each product type (process selection), determining maximum production levels of each product type (capacity planning), and locating production resources and routing of products to required resources (facility layout), are required in planning a manufacturing system. The importance of integrating these decisions was examined and the advantages of the integrated approach were illustrated. The structure of the suggested integrated model showed how the overall problem was decomposed, as well as the interactions between the decision problems [14]. Capacity Oriented Analysis and Design of Production Systems [15] is a book which has many chapters on the topic of capacity. An equation to calculate the production capacity specific to a product (acid-resistant wares) is given in ideal conditions [16].

Capacity is defined under three categories: design, effectiveness and actual capacity. Design or maximum capacity is the output that an operation can produce continuously, at the maximum rate without stopping. Effective or available capacity considers how the operation will run on a long-term basis, to include all planned stoppages. Actual capacity also includes unplanned stoppages. Actual output is effective capacity minus unplanned losses. Therefore, the operation which is working its assets efficiently is minimizing unplanned losses [17].

Data on capacity utilization in the U.S. economy is gathered and published by the Federal Reserve. Capacity utilization tends to fluctuate with business cycles; firms adjusts production volumes in response to changing demand. The Fed has published capacity utilization figures since the 1960s, spanning a number of economic cycles. In the late 1960s and early 1970s, all-time-high capacity utilization levels approaching 90% were achieved. The deepest declines in capacity utilization occurred in 1982 and 2009, when it fell to 70.9% and 66.7%, respectively [18]. See [19], [20] and [21] for more information.

2.2 Scaling up from Research to Production

While the ultimate goal is to go directly from process optimization to full scale plant, the pilot plant is generally a necessary step. Reasons for this critical step include: understanding the potential waste streams, examination of macro-processes, process interactions, process variations, process controls, development of standard operating procedures, and others. The information developed at the pilot plant scale allows for a better understanding of the overall process, including side processes. Therefore, this step helps to build the information base so that the technology can be permitted and safely implemented [22]. This paper focused on the specific needs of the operating plant to allow a new technology to be implemented.

The pathway of temperature increase during reaction, as well as adjustment of operating condition conducted for laboratory experimental data in order to produce a good quality of paste-glue was monitored while scaling up production from a 1,000ml reactor to a 500L pilot-scale reactor and a 1,500L near commercial scale reactor. Critical parameters for a good product quality, such as viscosity and ceiling temperature of the reaction, which are very crucial in order to give optimum operating condition as well as some scaling up parameters, have been found. The synthesis method of paste-glue production was selected and found the range of the parameters in order to produce a very good quality of paste-glue in pilot scale and near commercial scale [23]. In [24] the author explains how close R & D interaction was needed to design the production facility.

The review in [25] presents the challenges of up-scaling lentivirus production and processing approaches, novel systems for overcoming these issues, and the quality assessments recommended for producing a clinical grade lentiviral gene therapy product. In a chapter of the book [26], the authors have discussed different production hosts, process development, fermentation process, scale up, challenges in the scale up of biopharmaceuticals production, purification of biopharmaceuticals, and recent developments on scale up of biopharmaceuticals production. When transferring film manufacturing from lab-scale to continuous mode, film compositions, processing conditions and suitable characterization methods have to be carefully selected and adopted [27]. In [28], the authors deal with the technology transfer from a small-scale inkjet printing system to a pilot scale process by incorporating the same print head assembly into a continuous ODF production process.

In [29], a scale-up analysis of a dual cell photo reactor based on a kinetic radiation model and mass balance of reactants is presented. A kinetic model that includes phenomenological based parameters is developed to evaluate the reaction rate under operational conditions of a photo-reactor. The analysis is performed for six different scale-up ratios with three different constraints for each case. The analysis is followed by an exergoeconomic study in which two case scenarios of a hydrogen production plant, with and without oxygen production for three different production capacities, are considered. In [30], the authors explain how the reaction conditions were transposed from small reactor capacity to a large capacity reactor. The relevant parameters, which affect the yield and reaction time, are studied. Also [31] and [32] explain how research to production of molecular beam epitaxy was carried out. An additional source is [33] where the author explains how they overcame scale-up limitations of ultrasonic processing.

All of the articles/books mentioned above take a step by step approach to reach the full production. The presented approach in this dissertation goes from research to full production of the product quantity demanded directly, thus eliminating the trial and error steps in between.

2.3 Manufacturing System Design (MSD)

An ideal MSD is one in which the design satisfies a given set of constraints by the selection of functional requirements. It is time variant; selection of specific sets of functional requirements and constraints change the design. A subset of an entire manufacturing enterprise, as well as that of a production system, is a manufacturing system. Manufacturing enterprises consist of elements and the design of manufacturing systems are regarded to be complex. The various elements of manufacturing enterprise are machines, tools, material, people and information. The functional requirements (FRs) placed on the manufacturing system predicates the specific combination of a manufacturing system's elements [34]. There are four domains in the design world as per the axiomatic design approach. The domains are: the customer domain (customer attributes), the functional domain (functional requirements - FRs), the physical domain (design parameters - DPs) and the process domain (process variables - PVs). The construct of mappings among these domains is the design. Design requirements lead to conceptual design, followed by configuration design which will provide the detailed design. The design requirements are broadly classified as functional requirements and constraints. Determination of manufacturing operations, selection or initial design of machines that provide the required operations, determination of the type of manufacturing systems and identification of possible material handling systems, are included in the conceptual design. The conceptual design is refined by the configuration design where the machines are arranged into a system (layout design). All design parameters are refined at the detailed design stage and the final design is evaluated for implementation [35].

A physical system is required to manufacture a product whether it is in volume manufacturing or in a job shop. The inputs for the manufacturing system design are the task models (product/part/assembly/planning). MSD is comprised of workstations, layout planning, and throughput strategy. Product design is translated into manufacturing requirement by process design which leads to time and cost of manufacture. Both part planning and assembly planning require task analysis and hence their underlying unity. The interactions involved between the customer's requirements and the product's functional attributes makes product planning complex. The workstations provide concurrency of tasks, in physical systems, which is a requirement for the volume manufacture. The quantity (volume) of the product to be manufactured, shift time and total time of overall tasks determines the number of workstations. In order to meet the demands of equipment and transfer systems, layout arrangements of workstations are required. A significant part of the overall system design is the layout in high volume manufacturing. Large capital, that could be more effectively utilized, is tied up when buffer levels are significantly high. Lean manufacturing reduces the buffer levels to a minimum or eliminates them completely. It is an extension of just-in-time manufacturing which resulted from the need for continuous flow of production [36].

The high-level structure of the manufacturing system configuration is a collection of interacting components. The reconfigurable manufacturing systems are the most flexible and productive because they are based on standard/template sub-systems and elements [37]. A manufacturing system, which satisfies the strategic objectives of a company, needs to be designed according to the following four precepts: (1) Separate objectives clearly from the means of achievement, (2) Relate low-level activities and decisions to high-level goals and requirements, (3) Understand the interrelationships among the different elements of a system design, and (4) Effectively communicate this information across the organization. In TPS [3], the objectives and means are not clearly distinguished, its focus is on the physical tools (the means), the systems solution of which is predefined. The decisions about manufacturing system design are taken by relating high level design decisions to important system characteristics such as operational costs. How lower-level design decisions, such as equipment design and operator work content, affect system performance is not communicated. The low-level decisions to high-level system objectives are traced by the frameworks developed but they do not state the means to achieve the given objectives. Moreover, a strong design link between strategic objectives and the operational means to achieve them is not provided by these frameworks [38].

A closer integration of design, layout, process, and manufacturing within and across companies are needed (forced) because of the changes in manufacturing processes and the introduction of new materials. The paper examined extra structural features apparently added for Design for Manufacturability (DFM) purposes by a few manufacturers with similar products by comparing the old and the new products [39]. The same idea was presented in [40]. Phases where plans are implemented into reality bring forth problems in production management for the first time. Some examples are: when production commences, prototypes enter manufacturing and deliveries are expected. A study was conducted to see how the management can anticipate probable near future pitfalls by applying advanced visualization techniques to the existing information available with the companies. The problems identified in the analysis helped the companies to react in advance [41].

The focus of these research studies has been on the product/part or on improving the process and Manufacturing System Design (MSD) from a traditional perspective (physical design). None of the studies have researched applying the concept of reverse engineering to designing a manufacturing system. This dissertation will try to fill the gap in the application of reverse engineering to the design of a manufacturing system. This research focuses on the operational MSD rather than the physical MSD.

2.4 Operational Excellence, Variations, Disruptions and Flow

Operational Excellence (OE) is a philosophy of the workplace where ongoing improvement in an organization is undertaken by problem solving, teamwork, and leadership. The improvement is made by focusing on the customers' needs, keeping the employees positive and empowered, and continually improving the current activities in the workplace [42]. Some of the core principles of OE are: embrace scientific thinking, focus on the system process and think systematically [43]. Some of the methodologies used in OE are lean manufacturing, Six Sigma (identify and eliminate variation) and kaizen [43].

Variability exists in all production systems and can have an enormous impact on performance. Variability is anything that causes the system to depart from regular, predictable behavior. Variability causes performance degradation by inflating one or more of three buffers (stock, time, capacity). The two primitive elements that make up any production system are stocks and flows. A flow represents materials or resources moving through the transformation process and is essential. Flows refer to the transfer of jobs or parts from one station to another. A stock represents material or other resources waiting for transformation. Inventory buffers are kept in stocks while the other two buffers (time and capacity) are related to flows. Demand and transformation are two essential parts of a production system and are themselves a type of flow; demand is an inflow whereas transformation is an outflow. If demand and transformation are not perfectly aligned, there will be one or more buffers. The usual cause of misalignment between demand and transformation is variability. Variation is a measure to determine how the system conforms to the standards. The most prevalent sources of variability, which affects the effective process time in manufacturing environments, are: (1) Natural variability, which includes minor fluctuations in process time due to differences in operators, machines, and material, (2) Random outages, (3) Setups, (4) Operator availability and (5) Recycling [3].

The effects of variability in the overall production line can be characterized by process time variability and arrival variability. The variability, in the worst case, is completely predictable and results from bad control; while the variability in the practical worst case is due to unpredictable randomness. Controllable variations occur as a result of decisions, whereas random variation is a consequence of events beyond control. Variance (σ^2) and standard deviation (σ) are measures of absolute variability [3]. All parametric distributions will have variance and mean.

Lean Manufacturing often talks about reducing wastes by eliminating Non-Value-added tasks. Lean Manufacturing is an integrated socio-technical system which eliminates waste by using a systematic method [44]. In the current practice of lean implementation, most of the lean tool's focus is on time and material through techniques which rarely captures variability and tries to eliminate different sources [45]. Lower Throughput, congestion, high WIP levels, and longer lead times are a few of the examples of the effect due to variation. Variability is the enemy of manufacturing and the source of many of its problems [3], [45]. Design performance fluctuations could be caused by variations in the manufacturing process. Variations, if not accounted for, can cause a design to fail to meet performance and/or correctness criteria [46]. To identify the source of variation and to reduce it, a new technique similar to Value Stream Mapping (VSM) called Variability source Mapping (VSMII), has been developed. VSMII captures variation in terms of time and flow [45]. Production variability is less for many machines in series than in a single machine system in a production system with the same production volume and reliability characteristics as a longer line [47].

The variability of cycle times in semiconductor manufacturing lines is reduced by diminishing the magnitude of overtaking through appropriate sequencing rules [48]. By using sequencing rules like first in first out (FIFO), earliest due date, critical ratio and closest to completion by step overtaking can be reduced, but the reduction does not always lead to reduction in variation in cycle times. The variance of cycle time is also caused by the lots repeatedly returning at different stages of their production to the same service stations for further processing, consequently creating considerable competition for machines [49]. This leads to variation in cycle time at the workstations; to reduce this variation in cycle time the authors have proposed scheduling policies called fluctuation smoothing policies. By using these scheduling policies, the variance in cycle time can be reduced. Production variability, due to random disturbances, cause the observed production rate to be different from its average value; the evidence of which is in industries [50]. By using the method to estimate the problems causing the variability in a multistage manufacturing system, the relation between the output variance, the machine reliability parameters and the buffer sizes are obtained [50].

There are a few studies conducted about manufacturing cycle time (CT), lead time (LT) and also about queues in series. An approximation approach, based on observed properties of the behavior of tandem queues to find the queue times with variability in the line, is developed [51]. The waiting time (and hence manufacturing lead time) distribution and the mean performance measures are derived using the factorization principle [52]. A mathematical model focused on the manufacturing lead time and the utilization efficiency is derived [53]. An analytical model, which provides insights into the connection between the parameters (such as process time, arrival rate and placement of the inspection station) and performance (throughput, manufacturing lead time) of a manufacturing system is presented [54].

Disruptions can cause significant impact on the performance of a production system and can also lead to delays in delivery dates, impacting customers and widening delays in delivery dates, which also impacts customers and wider business functions. Some examples of disruptions are quality problems, resource breakdowns, material unavailability, order changes and rush orders [55]. In a production line that deals with interruptions due to lack of resources and product quality, it is necessary to analyze the steps for balance between Lean and resilience [56]. One of the major causes of disruption in production line is due to equipment. Absence of proper maintenance is one of the main reasons for disruptions and unavailability in the production equipment. Maintenance should be considered as a key variable in the construction of operations and infrastructure strategies and their varied impact on the production line should be considered [57]. Disruption is a state during the execution of the current operation, where the deviation from plan is sufficiently large, thus the plan has to be changed substantially. Just-in-time approach to production, aiming at increasing productivity and decreasing the cost of production, gives rise to an increased demand for robustness in plans and calls for enhanced tools to handle disrupted situations [58].

For the production to reach the necessary quantity, required quality, in the necessary time and with the most reasonable cost, the ways in which such an organization uses the production schedule is to be understood and thus organize rescheduling, scheduling and workflow while considering the disruptions in the schedules [59]. When disruption occurs, resistance against any change and rescheduling from the previous program may be shown by the internal system factors (e.g. operators) [60]. In airline management, the operators at the operations control center carry out the disruption management process in three steps: (1) They formulate the problem qualifying it in terms of resolution time, passengers impacted, delay propagation through the network and others. (2) Different options to resolve the situation are listed and ranked. (3) The most suitable solution is implemented [61]. When disruption is caused by an employee, it is usually due to heavy workload, labor shortages, lack of information and personal preparation which cause extensive interruptions in the workflow and delays in the schedule [62]. System Dynamics is a simulation modeling technique that was specially designed to model and explore feedback. System dynamics has been used for the analysis of cost or delivery overruns on large projects. The system dynamics model consists of three main work functions: design engineering, methods industrial engineering, and manufacturing [63].

2.5 CT, LT and TAKT time

CT is the actual time to do the processing; LT is set by the management whereas TAKT time is set by the customer. Value Stream Mapping is a lean tool used to greatly reduce cycle time, as well as lead time. An application of VSM in an OEM is provided by the authors [64]. VSM, as a lean tool, has been used to reduce the cycle time by identifying and eliminating wastes in a facility with similar or identical product routing. VSM, along with Methods-Time measurement (MTM), are used to reduce lead time and increase the productivity in an assembly and production-logistic processes. A practical example is used to highlight the redesign of assembly workplaces and the redesign of production logistic processes to reduce the inventory/ lead times and increase the productivity by standardization of process [65]. Efficient Scheduling policies are also used to reduce mean and variance of cycle time in a semi-conductor manufacturing plant. Use of new class scheduling policies, called fluctuation smoothing policies, helped achieve the best mean cycle time and deviation of cycle time in all the configurations of the plants that were tested [49]. Cycle time reduction has also been studied in a semi-conductor wafer fabrication facility in which the method developed by authors managed to reduce the cycle time, increase the capacity and reduce the WIP [66]. Agility is the power to cope with the variability and uncertainty in the market or virtual corporation. Two main factors affecting the supply chain are waste Total Cycle Time (TCT) and waste information flow [67].

The information enriched supply chain can reduce the lead times for information and material flow and the total cycle time will reduce if the supply chain is more agile. The factors that are controllable by the company and affect the Total Cycle Time (TCT) are purchasing cycle time, design and manufacturing cycle time, inbound transportation cycle time and outbound transportation cycle time. Various aspects related to the above mentioned factors are discussed and theories are developed to reduce the TCT [68] . Short manufacturing cycle times are required for a firm to meet short lead times, without excessive inventories [69]. A good way to reduce the cycle time without increasing the company's expenses is by including an inventory of spare components. This reduces the time for maintenance and repairing, thereby reducing the cycle time. The proper amount of spare parts inventory, such that the inventory costs are justified, is discussed by the author based on the following five factors: (1) mean time to failure for both single and multiple critical components, (2) critical component replenishment lead times, (3) workstation arrival rates and variances, (4) critical component annual holding costs, and (5) hourly revenue increases for cycle time reductions [69].

2.6 Effects of Variation, Disruption on CT

A discussion about the Factory Physics [3] approach to study the effect of variation on CT is given here; increasing variation increases CT, placement station with variations and propagation of variation impact CT. The formulations in the theory are used in the development of the mathematical model for TF in Section 3.2 of this dissertation. Variation and disruptions are closely connected in the literature through the availability of resources (such as equipment, people and material). Line performance is measured by SL as shown in Equation 2.1 [3].

$$SL = P\{CT \leq LT\} \qquad 2.1$$

Capacity is an upper limit on the TH of a production process. TH can be increased by increasing the utilization of the bottleneck or its rate. Bottleneck is defined as the busiest station (highest utilization), not necessarily the slowest station. Utilization of the bottleneck can be increased by buffering it with WIP [3]. It can also be increased by reducing the variations and disruptions in the bottleneck; as well as by enhancing capacity. TH of a line is given by Equation 2.2 [3].

$$TH = bottleneck\ utilization\ \cdot bottleneck\ production\ rate \qquad 2.2$$

Utilization (u) (Equation 2.3) is the ratio of the arrival rate (r_a) to the effective production rate (r_e). The effective production rate is defined as the maximum average rate at which the workstation process parts considering the effects of failures, setups and all other detractors that are relevant [3].

$$u = \frac{r_a}{r_e} \qquad 2.3$$

The critical WIP (W_0) of the line [3] (Equation 2.4) is the WIP level for which a line with given values of r_b (bottleneck rate) and T_0 (raw process time), achieves maximum throughput with minimum cycle time, when there is no variability. T_0 of the line is the sum of the long-term average process times of each workstation in the line. It is the average time a single job takes in the empty line [3].

$$W_0 = r_b \cdot T_0 \qquad 2.4$$

Stable system requires the input to the system not exceed its capacity. The capacity of a line must be at least as large as the arrival rate to the system. When a production system has variability, then, a sequence of events will cause the system bottleneck to starve (run out of WIP) regardless of the WIP level. A steady state system avoids this. In steady state, all plants release work at an average rate which is strictly less than the average capacity. If there is no limit as to how much WIP can be in the system, both CT and WIP go to infinity as utilization approaches one. If a station increases utilization without making any other changes, average WIP and CT will increase in a highly nonlinear fashion [3]. If V is the variability, U the utilization and T the time respectively, then the mean time spent in queue (CT_q) is given by Kingman's Equation [70], [3] in 2.5 .

$$CT_q = V \cdot U \cdot T \qquad 2.5$$

The coefficient of variation (CV) is the ratio of standard deviation (SD (σ)) to the mean (μ) as shown in Equation 2.6 [3]. The CV is also denoted as σ/t if the random variable considered is time (here t denotes the average of time).

$$CV = \frac{\sigma}{\mu} \qquad 2.6$$

The processes are classified as low variability (LV), medium variability (MV) or high variability (HV) depending upon the value of the CV. LV processes will have their CV< 0.75, whereas MV process will have 0.75 ≤ CV ≤ 1.33 and process will be HV when their CV > 1.33 [3]. The probability density function (pdf) of most LV processes are bell shaped (normal distribution) [3].

One important measure of variability is in the process time. Effective process time of a job at a workstation is the total time *seen* by a job at a station. If A is the availability of the machine, t_0 is the natural process time, m= number of machines in parallel at that station and r_0 is the natural capacity (rate), then mean effective process time (t_e) [3] is given by Equation 2.7 whereas the capacity or rate of workstation r_e [3] is given by Equation 2.8. The CV of effective process time (c_e) [3] is given by Equation 2.9 where m_r is the meantime to repair, c_0 is the natural CV of the process and c_r is the CV of repair. The three terms, in Equation 2.9 denote natural variability, random outages and variability of repair time respectively [3].

$$t_e = \frac{t_0}{A} \qquad 2.7$$

$$r_e = \frac{m}{t_e} = A \cdot \left(\frac{m}{t_0}\right) = A \cdot r_0 \qquad 2.8$$

$$c_e^2 = c_0^2 + A(1-A) \cdot \frac{m_r}{t_0} + c_r^2 \cdot A(1-A) \cdot \frac{m_r}{t_0} \qquad 2.9$$

The cycle time of the queue (CT_q) for a single machine station is given by equation 2.10 where c_a = CV of inter arrival time. The CT_j is the sum of CT_q and t_e (equation 2.11) which leads to Equation 2.12 . The CT_{line} is the summation of the CT_j of all stations in the line [3], [54] as shown in Equation 2.13. Any overlap in time between stations is to be deducted.

$$CT_q = \frac{c_a^2 + c_e^2}{2} \cdot \frac{u}{1-u} \cdot t_e \qquad \text{where } u = \frac{r_a}{r_e} \qquad 2.10$$

$$CT_j = CT_{qj} + t_{ej} \qquad 2.11$$

$$CT_j = \frac{(c_{aj}^2 + c_{ej}^2)}{2} \cdot \frac{u_j}{1 - u_j} \cdot t_{ej} + t_{ej} \qquad 2.12$$

$$CT_{line} = \sum_{j=1}^{m} CT_j \qquad 2.13$$

In Equation 2.12 the average queue and CT grows to infinity as utilization approaches 100 percent. Queues never become infinite in the real world because of limitations of space, time or operating policy. **Whenever any of the limits are reached, the arrival process is stopped. This procedure is called blocking**. By employing blocking, the stream of work from the previous station to the station where the limit is reached, is cut off [3].

The G/G/1 queuing model (CT equations has CT_q related to the queue) is more appropriate for manufacturing systems as noted by the authors of Factory Physics [3]. In G/G/1 queue, the system with a single server, the inter-arrival times and service times have a general distribution. When workstations are fed by upstream stations whose process times are not exponential, the inter-arrival times also are not likely to be exponential. Process times are seldom exponential [3]. The variance and mean of the normal, triangular and uniform distributions, which are common in manufacturing operations, are provided in Table 20 Appendix B. Also presented in Appendix B ([71] and [72]) are some of the common distributions. An example of the calculations of mean and CV for a triangular distribution are given in Table 21 Appendix C.

When the variability at one station affects the behavior of other stations in a line, it is referred to as flow variability. If an upstream workstation has highly variable process times, the flows it feeds to downstream workstations will also be highly variable. The variability in flow is characterized by arrivals and departures. Variability in departures from a station is the result of both variability in arrivals to the station and variability in the process times. The relative contribution of these two factors depends on the utilization of the workstation. The actual process time typically represents only a fraction of the total CT. The majority of the remaining time is spent waiting for various resources/activities [3]. This flow variability is also referred to as propagation of variation.

If CV of arrival at a particular process is denoted by c_a, the CV of the process is denoted by c_e, the CV of departure from that process is denoted by c_d and the number in the subscript denotes the location, then from [3] Equations 2.14 to 2.16 are obtained. This can be generalized as shown in Equation 2.17.

$$c_{d1}^2 = u_1^2\, c_{e1}^2 + (1 - u_1^2)\, c_{a1}^2 \tag{2.14}$$

$$c_{d2}^2 = u_2^2\, c_{e2}^2 + (1 - u_2^2)\, c_{a2}^2 \tag{2.15}$$

$$c_{a2} = c_{d1} \tag{2.16}$$

$$c_{aj}^2 = c_{dj-1}^2 = u_{j-1}^2\, c_{ej-1}^2 + \left(1 - u_{j-1}^2\right) c_{aj-1}^2 \tag{2.17}$$

This shows that the effect of variation propagates through the system. Variation at a station will affect the next immediate station and subsequently the whole system. If the arrivals at the first station can be tightly controlled ($c_{a1} = 0$) then the departure variation from the first station will be the result only of the variation in the process itself and the utilization of that station.

Queue time is impacted by the utilization of the machines, the process time, the coefficient of variation of arrival time, as well as process time. This queue time in turn affects the CT. Also, the availability of resources determines the effective process time. The coefficient of variation of arrival time at a station is dependent on the coefficient of variation of departure time of the previous station. Variability and disruptions affect the CT and hence the TH. <u>The effect of variability can be reduced by cutting down the disruption in the process and by reducing queue time.</u> WIP and CT can be reduced by anything that enables jobs to move from one workstation to the next, with less waiting [3].

If a station has to wait for a number of batches to be processed at the previous station, then there is a Transfer Wait Time (TWT) which is based on the batch processing equation of Factory Physics [3]. If the number of batches at a station is denoted by X_{2j} and the utilization of the station is denoted by u_j, then the TWT is given by Equation 2.18.

$$TWT = \frac{X_{2j} - 1}{2 * u_j} \cdot t_j \qquad 2.18$$

The TWT will be exactly equal to the real wait time for batching, only when the utilization of the station is 50%; if the utilization is more than 50%, then the TWT will be less than the actual batch wait time and vice versa. If there is no batching (X_{2j} =1), the TWT will be zero.

When there is batch processing in any of the station(s) and the subsequent stations process multiple batches (X_{2j}) from the previous station at the same time (one process for multiple batches), then the CT of the station with batch processing will be (applying Equation 2.18) as given in Equation 2.19.

$$CT_j = \frac{(c_{aj}^2 + c_{ej}^2)}{2} \cdot \frac{u_j}{1 - u_j} \cdot t_j + \frac{X_{2j} - 1}{2\, u_j} \cdot t_j + t_j \qquad 2.19$$

TH is dependent on cycle time (CT) and Work-In-Process (WIP) as per Little's law [5] (Equation 2.20). A system with short CT and low WIP is preferable.

$$TH = \frac{WIP}{CT} \qquad 2.20$$

Reduction of variation will result in a reduction of CT. The theory and the equations discussed above are used and modified in the computational development for TF in Section 3.2. The appropriate type of probability distribution in the manufacturing operations will be represented by its CV (ratio of the standard deviation to the mean) in the time to finish Equations 3.17 and 3.19.

2.7 Summary of Literature Review

The literature review concludes that the effect of variation and disruption issues on the timely completion of processes are not considered when systems are designed but are considered as continuous improvement projects once the processes are running. Manufacturing systems are designed primarily with focus on machines and their physical layout, not on the operational aspects. Production reaches the estimated demand quantity (capacity) in stages through step by step scaling up activities; there is no systematic approach to scale up directly from the research to the quantity demanded. Capacity of a plant is not computed based on the timely completion of the processes and comparing with the time allocated. The concept of TF vs TA combination is not studied and as such has not been used; if the processes get completed within the time available, then there is sufficient capacity to meet the demand. The various studies about the effect of detractors (such as variations, disruption and flow related issues) focus on CT vs LT combination. The effect of variation and disruption on CT is available in the literature. Additional literature review (Appendix D) was done to check whether re-engineering or reverse engineering has been used in designing operational manufacturing systems. It was used in product/process design or for making improvements but not for designing manufacturing systems. This dissertation has not applied it either but it could be applied for future expansion work of this dissertation.

3
METHODOLOGY

In this chapter, the framework to study and design operational manufacturing systems is discussed in detail. The development of the mathematical model which computes the time to finish (TF) is given. The methodology considers the effect of variation and disruption issues at the design stage itself focusing on the sources which are the “four critical resources” [6] explained in Section 1.5.1.

The focus in the literature is on the cycle time (CT) and lead time (LT) as shown in Section 1.3 and Chapter 2. From a CT perspective, the key manufacturing metrics are CT, throughput (TH), Capacity and Service Level (SL). The theory about CT and its formulation was discussed in Section 2.6 and the TF concept is based on this theory. This model concentrates on the TF concept, which is a novelty and a main contribution of this dissertation. In government manufacturing, since the facilities are often shared between different products, time allocation for the production of a particular product is mostly very rigid; also because of security issues the materials are not allowed to be left in the manufacturing areas of the facility. Hence quantification of TF is useful in checking whether the production processes can be completed within the time allocated (TA). The computation of TF will also help in determining whether the suggested operations are practically feasible. Moreover, time allocation might not be continuous; it could be in different periods. The detailed definition of CT, LT, TA and TF are given in Section 1.3.

The key manufacturing metrics from the TF perspective are TF, TH, Capacity and SL. The formulation of TF developed for this dissertation is discussed in Section

3.2. The TF is not a constant (because of randomness, variation and disruption issues) whereas the TA is a constant set by the owner of the facility. The TF is not the same as CT even if the manufacturing time is continuous Section 1.3 Figure 1.1). In the TF approach there are more startups, setups, cleanup, and shutdown activities if the manufacturing is spread over different periods compared to one single continuous allocation of time. Shutdowns are more specific because material cannot be left in the manufacturing facility. This causes greater variation and disruption into the system compared to a single continuous period of time allocation. In a normal multi-period manufacturing, the process will continue from where they were left over in the previous period. Here, because of the constraint that there cannot be any material leftover, the planned production quantity is to be finished in the period itself.

In order to evaluate the performance of a system, SL is a commonly used metric. In the literature SL is determined by the CT versus (vs) LT combination and with a similar analogy, in this dissertation TF vs TA is evaluated. SL is an indication of capacity. Capacity is then defined by TF vs TA combination rather than CT vs LT combination. In this model, the TF, when compared with the TA, will determine the capacity. In general, TF is greater than CT; TF is equal to CT only when the entire demand can be met in a single production run.

For this dissertation, the demand is certain and known. Hence the TH is set equal to the demand; the model is focused on meeting the demand by computing the TF. TH is now connected to TF; if the TF is less than TA, then the TH from the system will be able to meet the demand and hence there is sufficient capacity.

Little's Law [1] uses CT and WIP to explain TH. TH is now explained by the WIP and TF (TH = WIP/TF). This is a modification of Little's Law. This chapter will provide the detailed logic associated with the model for TF which ensures that the capacity exists to meet the demand. This allows the designers of manufacturing systems to have a detailed insight in the initial stages of the design life cycle of the operations of manufacturing systems.

3.1 Roadmap and Framework

The framework shown in Figure 3.1 starts by analyzing the present capacity and checks whether the existing capacity can meet the demand in ideal conditions. The first block in the model is phase 1 whose objective is to check the existing capacity of the system using TF and TA. The ideal condition TF is computed using Equation 3.15 which checks the existing capacity of the system. This phase is described in Section 3.4.

The core section of this model (phases 2, 3, 4 and 5) is the second block where operational excellence design is carried out. This block defines the key opportunity to reduce TF. This design attempts to decrease TF to a level where TF<TA. By reducing variability (identifying the sources and taking corrective actions), minimizing disruptions and by designing flow, the TF can be decreased.

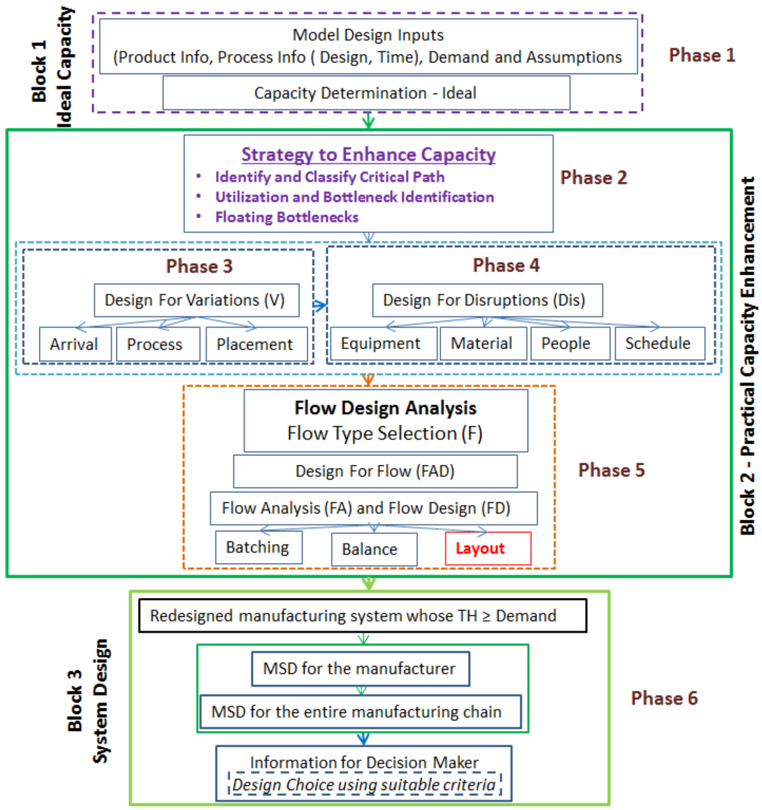


Figure 3.1 Model Framework

The key objective of phase 2 is to identify the weakness in the system that can be exploited to decrease TF. This is done by: (1) identifying the critical path, (2) classifying the critical path, (3) computing utilization of stations, (4) identifying the bottleneck station(s) and recomputing the ideal conditions TF using utilization of stations as a new variable employing Equation 3.16. This phase is explained in Section 3.4. The objective of phase 3 is to identify variation issues and its sources, its impact on TF and hence capacity. Detailed description of this phase is in Section 3.5. The objective of phase 4 is to consider disruptions in the operational aspects of a system, its effect on TF and hence the capacity. A detailed explanation of this phase is in Section 3.6. Flow design (phase 5) is described in Section 3.7. Here the focus is in line balancing (if possible) and a single piece flow (or reduced batch size), if the facility infrastructure allows that, to reduce TF. The outputs from phases 2 to 5 are stored and are used simultaneously for the computation of the time to finish. The algorithms for phases 2 to 5 are discussed in Chapter 4.

The output of this model (phase 6) will be an operational manufacturing system design that ensures that by selecting the possible minimum TF the throughput will meet the demand to its best ability. It will estimate the time required by the other manufacturers in the product manufacturing chain. This output will allow a determination to be made whether capacity exists and if it does not, to formulate mitigating decisions. The output forms the basis to make the manufacturing decisions by the organization as explained in Section 3.8.

3.2 Mathematical Model for TF

This section presents the mathematical model developed. Based on the theoretical background of CT from the literature discussed in Section 2.6, the mathematical model is developed, which computes the TF considering all the factors related to variation, disruptions and flow issues to the extent possible. TF is not the same as CT; the former is corresponding to completing the entire demand, whereas the latter represents completion of each unit or batch.

Consider a product(s) whose manufacturing processes are sequential. There are n units (Mfgr) in the manufacturing supply chain (Mfgr.1 to Mfgr.n), each of which has their own processes for the conversion of their input materials to their product as shown in Figure 3.2. The output product from a manufacturing unit is the input

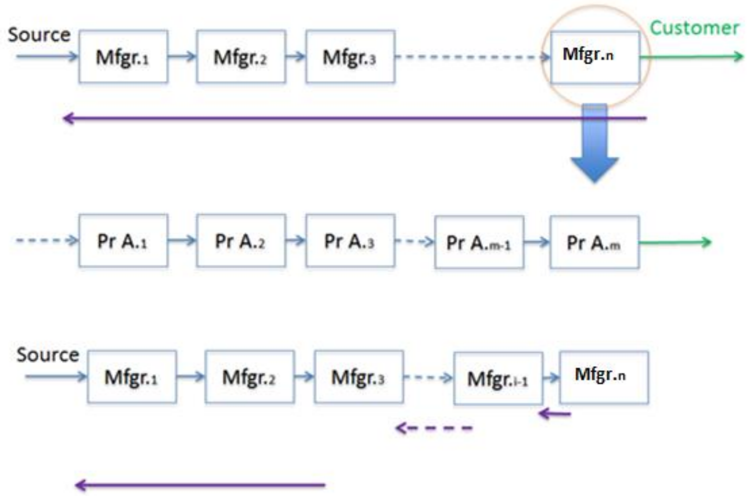


Figure 3.2 Manufacturing Supply Chain

material for the subsequent unit. Assume there are m stations or process areas (denoted by Pr A.i; i = 1 to m) for Mfgr.n. Similarly, all the manufacturers have their own processes which occur inside their process areas. Once the Mfgr.n is studied, the previous station is looked at until the first manufacturer in the line is reached. 'Process Area' is a term which is used to represent stations; some processes cannot have direct human contact (process interventions are carried out remotely) and the term process area will be more suitable than station. This dissertation's TF approach focuses on the last manufacturing unit.

3.2.1 List of Variables and Constraints

The variables and constraints are given below:

A) Y - Demand or required output quantity (known)

B) MR_1 - Material required for one unit of the product

C) X_{TOT} - Total Material Required: calculated from MR_1 and the demand

D) X_{1j} - Quantity per batch: j denotes location of process area; j = 1 to m

$1 \leq X_{1j} \leq n_{1j}$: n_{1j} denotes the capacity at that process area

E) X_{2j} - Number of batches

F) X_3 - Number of production runs

X_{2j} and X_3 will be between 1 and a value specified (n_{2j} and n_3 respectively).

G) $X_{1j} \cdot X_{2j}$ - Quantity per batch

H) t_j - Processing times at each process area: j=1 to m; (t_1, t_2………… t_m. t_j is the time to produce a single unit/batch (if the entire batch takes the same time irrespective of the batch size)

I) t_{sj} - Set up time at each station: j=1 to m

J) t_{cj} - Cleanup activities at each station before the next processing: j=1 to m

K) t_{on} - System start up time

L) t_{off} - System shutdown time

M) c_{aj} - CV (coefficient of variation) of arrival at station j

N) c_{ej} - CV of the process at station j

O) u_j - Utilization of the station j

P) A_E - Availability of equipment (station)

Q) A_M - Availability of material

R) A_P - Availability of people:

S) A_S - Availability of information / schedule:

T) A - Availability of the whole system;

U) TF - Time to Finish

TF < TA : TA is the Time Available

U.1) TF_i – ideal conditions TF without station utilizations considered; here '$_i$' is a subscript not an index.

U.2) TF_{ideal} – ideal conditions TF with station utilizations considered

U.3) TF_V – TF with variations

U.4) TF_D – TF with disruptions

U.5) TF_{VD} – TF with both variations and disruptions

The equations for TF require some elements (number of production runs, the number of batches per run and the batch size which is dependent on the other two variables) of the flow design. Hence TF equations will include flow design also to an extent.

3.2.2 Model Equations

TF is not constant (because of randomness, variation and disruptions factors) as shown in Equation 3.1. If the arrival processes are controlled, then the variations affecting the TF are effectively caused by set up changes and process variations. Propagation of variation affects the arrival variation from the second station onwards.

$$TF = fn(\, c_{aj}\,, c_{ej}, u_j, t_{ej}, \#\, batches\ per\ run, \#\, production\ runs, \quad WT_{factor}) \qquad 3.1$$

The service level equation from the literature is rewritten considering the TF concept. The TF is compared with TA. This comparison is called capacity to meet demand (CapDem) which is defined as the probability of TF compared with TA as shown in Equation 3.2. **The facility will be able to meet the demand only when Equation** 3.2 **is satisfied.**

$$CapDem = P\{\, TF < \ TA \,\} \qquad 3.2$$

When TF ≥ TA, the facility cannot meet the demand. As a result, the probability that TF < TA should be 1. This is ensured by selecting only the production options which results in TF<TA. Only when TF<TA, the requirements that all production operations should be finished within the TA and that no materials are allowed to be left over in the system be met.

Since the time to finish is the main focus of this study, the model equations from here start with the computation of time to finish for the last manufacturer in the chain. The development of the equations is presented starting with the concept of a perfect manufacturing system. A perfect system is one which has no variation, no disruption, a perfectly balanced processing line, and with a single piece flow arrangement ; single piece flow is found to be more effective to respond to changes faster and to reduce variations [2]. The effects of detractors (variations, disruptions) will be added later on.

Since the TH is set equal to demand (this is known), the model will be looking to compute the actual TF. This TF, when compared with the TA, will determine whether the system has the capacity to meet the demand. If the time allocated is continuous, then the TF will be computed only once. The TF will be computed for each period (if the time is allocated over different periods); the equations will remain the same, but the demand will be different. The values of t_{on} and t_{off} (which represent startup and shutdown times of the facility) as well as t_{sj} and t_{cj} (set up and cleanup activities for each station) will be applicable for each period of production (p = 1 to P) and hence the TF to manufacture Y units of the product will be much more if the production is carried out over many periods rather than one single continuous period. The selected option (for each period, there will be different possibilities with different TF (depending on the value of variables X_{1j}, X_{2j}, X_3); based on the computed TF a selection decision is to be made which has the lesser TF for each period is added to get the time to finish for the production of Y units. The values of the variables (X_{1j}, X_{2j}, X_3) for each period may be different; also the TF in one of the periods (corresponding to the same value of variables) may not be acceptable (if TF>TA) especially if the TA is not the same in different periods and the demand may not be the same in different periods and as such a double summation in the equation may not be useful.

Two classes of products were considered: (1) one which is used in single units of products (a vehicle as an example) and (2) consumed in quantities required by the consumer (liquid products or chemical processing as examples). The perfect system for the first class of product was defined already. The perfect system for the second class of product is one which has no variation, no disruption, a perfectly balanced processing line, a perfectly balanced processing capacity of the stations, and a quantity flow (dictated by the size of the containers in which the processing occurs). The different formulations developed for the model is summarized in Table 1 followed by the detailed steps. The suitable equation from the list is to be used depending on the type of system and environment in which it operates.

Table 1 Scenarios of Model Formulation

Equation Number	**Perfect System (Single Piece Product)**	**Perfect System (Liquid Product) – Unlimited processing capacity stations**	**Station processing capacity limited and unbalance capacity of stations**	**Batch processing and single piece processing stations together**	**Batching Effect Using FP perspective**	**Inventory Buffer Restrictions (Empirical)**	**Variation**	**Disruptions**	**Variations and Disruptions**
3.4	**Y**	N	N	N	N	N	N	N	N
3.6	N	Y	N	N	N	N	N	N	N
3.9	N	N	Y	N	N	N	N	N	N
3.11	N	N	N	**Y**	N	N	N	N	N
3.13	N	N	**Y**	**Y**	N	N	N	N	N
3.15	N	N	**Y**	**Y**	N	**Y**	N	N	N
3.16	N	N	**Y**	**Y**	**Y**	**Y**	N	N	N
3.17	N	N	**Y**	**Y**	**Y**	**Y**	**Y**	N	N
3.18	N	N	**Y**	**Y**	**Y**	**Y**	N	**Y**	N
3.19	N	N	**Y**	**Y**	**Y**	**Y**	Y	**Y**	**Y**

3.2.2.1 Perfect System

In the case of having a system in which production with single piece flow is possible (first class of product), the TF for Y units of product is given by Equation 3.4. Production starts at station1 and then it moves to the subsequent station; station1 starts processing again; it doesn't wait for the product to move through all the stations (see Figure 1.1). It is assumed, for this dissertation, that t_{on}, t_{off}, t_{sj} and t_{cj} are constant and are the expected values.

$$TF_i = t_{on} + t_{s1} + Y \cdot t_1 + t_{c1} + t_{s2} + t_2 + t_{c2} + \cdots t_{sm} + t_m + t_{cm} + t_{off} \qquad 3.3$$

$$TF_i = t_{on} + (t_{s1} + Y \cdot t_1 + t_{c1}) + \sum_{j=2}^{m} (t_{sj} + t_j + t_{cj}) + t_{off} \qquad 3.4$$

Further development focuses on the second class of product discussed. The model starts with a system which has unrestricted (unlimited) processing capacity at all stations followed by different types of capacity restrictions introduced.

Unlimited Processing Capacity: - If there are no capacity restrictions and all the stations (process areas) are capable of processing the entire demand at once (in a single batch and single production run), then the TF_i is given by Equations 3.5 and 3.6.

$$TF_i = t_{on} + (t_{s1} + t_1 + t_{c1}) + (t_{s2} + t_2 + t_{c2}) + \cdots + t_{sm} + t_m + t_{cm} + t_{off} \qquad 3.5$$

$$TF_i = t_{on} + \sum_{j=1}^{m} (t_{sj} + t_j + t_{cj}) + t_{off} \qquad 3.6$$

The TF for a perfect system is the sum of the individuals processing times, when there are no restrictions. The TF here is equal to the CT because there is only one production run.

With the objective of studying the real system, the model requires some variables which are to be computed first. The total material required (X_{TOT}) is calculated by Equation 3.7, based on the material requirement for one unit of the product ((MR_1)) and the demand (Y). Then depending on the processing capacity of the stations, the number of production runs (X_3) and the number of batches per production run (X_{2j}), the batch size (X_{1j}) are determined using Equation 3.8. X_{2j} and X_3 are needed in the model for TF from the next step onward. The WIP in each run will be determined by the batch size and the number of batches. The calculation of X_{TOT} is needed only in the case of some products where the materials for many units of the product are compressed to one single unit. An example would be nuclear products, many units of the materials are compressed for ease of operations. In other cases, Y itself is divided into X_3, X_2 and X_{1j}. The bill of materials considered for the product (such as chemical products) is limited to one level. If there are yield issues, then the targeted production quantity should reflect it (Y should be modified to adjust for the yield issues). This mathematical model does not consider any yield issues which will reduce the product quantity manufactured.

$$X_{TOT} = MR_1 \cdot Y \qquad 3.7$$

$$X_{TOT} = X_{1j} \cdot X_{2j} \cdot X_3 \qquad 3.8$$

The way X_{1j}, X_{2j} and X_3 are determined are as follows: An algorithm, written in MATLAB, searches for all possible combinations within the specified limits (X_{2j} = 1 to n_2; X_3 = 1 to n_3). For example, if n_2 & n_3 are set to 100 each (which results in 10,000 combinations), then it computes the value of X_{1j} from the equation $X_{TOT} = X_{1j} \cdot X_{2j} \cdot X_3$ and compares the computed value of X_{1j} with the physical capacity at that location (n_{1j}). Only if $X_{1j} \leq n_{1j}$ will that particular X_{1j} be selected; otherwise it will be discarded. A binary variable (1/0) is used to select the feasible (1) versus non-feasible (0) in the coding. An implementation of this determination is given in Appendix C which is associated with the algorithm for a level batch size decision.

3.2.2.2 Real Systems

In reality, there is no perfect system. . Production lines may be unbalanced with respect to both processing time and physical capacity, there could be buffer restrictions, and different types of processing may exist in the same line.

Capacity restrictions - Three types of restrictions are considered: (1) Batch processing capacity at stations, (2) Single Piece processing station in the line with other stations of batch processing type and (3) Inventory Buffer restrictions at stations.

1. Batch Processing Capacity Restriction - Assume that process areas cannot manufacture everything at once. If process area ‘a’ (Pr A.a) (location ‘a’; which is one of the stations in j = 1 to m; a ∊ j) has the processing capacity restriction (quantity) of n_{1a}, (**processing time of station at this location is the same for 1 unit or n_{1j} units or any number of units in between**), then the time at that area is (X_{2a}*X_3)*ta. The quantity for X_{1a} will be determined by X_2 and X_3 such that X_{TOT} = X_{1a}*X_{2a}*X_3 and X_{1a} should be ≤ n_{1a}. The cycle time of the line [3], [54] as given by the Equation 2.13, is expanded by introducing the number of productions runs (X_3) and the number of batches per run (X_{2a}), so that the entire demanded quantity is covered to obtain the TF_i. The TF_i with batch processing capacity restriction can be computed using Equation 3.9. Assuming that only j = 1 has this capacity restriction (this is the bottleneck); then TFi can be written as Equation 3.10. The TF_i with batch processing capacity restriction is the sum of the individual station processing times and the time the station with capacity restriction takes to process the whole material required. If there is more than one station in the line with unbalanced capacity, then the batching repeats at the other station, rather than only at station a.

$$TF_i = t_{on} + (t_{sa} + \left(X_{2a} \cdot X_3\right) \cdot t_a + t_{ca}) + \sum_{\substack{j=1 \\ j \neq a}}^{m} \left(t_{sj} + t_j + t_{cj}\right) + t_{off} \text{ ; where } a \in (1, m) \qquad 3.9$$

$$TF_i = t_{on} + (t_{sa} + \left(X_{21} \cdot X_3\right) \cdot t_1 + t_{ca}) + \sum_{j=2}^{m} \left(t_{sj} + t_j + t_{cj}\right) + t_{off} \qquad 3.10$$

2. <u>Single Unit Processing Station</u> - Some of the stations in the line could be of a single piece processing type whereas other stations are batch processing types. Assume that Pr A.b (location 'b', which is a station in j = 1 to m; b ∈ j) is a station which processes one unit at a time and that the processing time is t_b for each unit of product. If the whole customer required quantity reaches the station at once, the station processing time is Y * t_b. The chances of this are very low because there may be processes with restricted batch processing capacity ahead of this stage. In this way, the time at each process area is to be calculated taking into account for capacity /technology restrictions at every stage and the total time is to be computed as in Equation 3.11. The processing time of a single unit is (t_b) at station b. The TF_i in this case is given by Equation 3.11. Assuming that j=m has this type of capacity restriction; TF_i can be represented as in Equation 3.35. If there is more than one piece processing type station interlined with batch processing stations, then the equation should reflect it rather than only at station b.

$$TF_i = t_{on} + \sum_{\substack{j=1 \\ j \neq b}}^{m} (t_{sj} + t_j + t_{cj}) \ + (t_{sb} + \ Y \ \cdot t_b \ + t_{cb}) \ + t_{off} \quad \text{; where} \quad b \in (1, m) \tag{3.11}$$

$$TF_i = \ t_{on} + \sum_{j=1}^{m-1} (t_{sj} + t_j + t_{cj}) \ + \left(t_{sm} + \frac{Y}{X_3} \cdot t_m + t_{sm} \right) + \ t_{off} \tag{3.12}$$

Combining both the restrictions (if a line has both types of stations) represented in Equations 3.9 and 3.11 will give the Equation 3.13, a variation of which was presented in [73]. This equation is the combination of the summation of the processing times of stations with no restrictions, the total processing time of the station with capacity restriction, and the time the single unit processing capacity station takes. Here the entire demand will not arrive to station b at once; instead the quantity arriving at its input every time is Y/X_3 only.

$$TF_i = t_{on} + \left(t_{sa} + X_{2a} \cdot X_3 \cdot t_a + t_{ca}\right) + \sum_{\substack{j=1 \\ j\neq a \\ j\neq b \\ a\neq b}}^{m} \left(t_{sj} + t_j + t_{cj}\right) + \left(t_{sb} + \frac{Y}{X_3} \cdot t_b + t_{cb}\right) + t_{off} \quad ; \text{where } a, b \in (1, m) \tag{3.13}$$

Assuming that Pr A.1 (a=1) has a batch processing capacity restriction and Pr A. m (b=m) is a single unit processing station; then the Equation 3.13 can be written as in Equation 3.14 below.

$$TF_i = t_{on} + \left(t_{s1} + (X_{21} \cdot X_3 \cdot t_1) + t_{c1}\right) + \sum_{j=2}^{m-1} (t_{sj} + t_j + t_{cj}) + \left(t_{sb} + \frac{Y}{X_3} \cdot t_b + t_{cb}\right) + t_{off} \tag{3.14}$$

3. <u>Inventory Buffer Restrictions</u> - The Equation 3.13 assumes that the production line is perfectly balanced. Processing time of the stations being significantly different causes line imbalance, which can be managed only by having a buffer between the stations (unless process can be changed so that the processing time at each station are the same). If the production line is not balanced and if the WIP between the stations is restricted, then each station may have to wait for further operations if the subsequent station is not available. This leads to another type of restriction which is related to inventory buffer (storage) between stations (referred to as blocking in Factory Physics [3]). To accommodate for this, a waiting time factor (WT_{factor}) is to be added to the TF as shown in Equation 3.15.

$$TF_i = t_{on} + \left(t_{sa} + (X_{2a} \cdot\ X_3 \cdot t_a)\ + t_{ca}\right) + \sum_{\substack{j=1 \\ j\neq a \\ j\neq b \\ a\neq b}}^{m} (t_{sj} + t_j + t_{cj})\ + \left(t_{sb} + \frac{Y}{X_3}\ \cdot t_b + t_{cb}\right) +\ t_{off} + \quad WT_{factor} \quad \text{; where } a, b\ \in (1, m) \tag{3.15}$$

<u>**Estimating Waiting Time Factor**</u> - There are two main categories to be considered in determining the waiting time factor: (1) when there is only one production run – the WT_{factor} is zero (0) because the subsequent production areas are available and (2) when there is more than one production run. The WT_{factor} was estimated as: $WT_{factor} = (X_3)^2/X_2$ or $(X_3)^3/X_2$. The latter is applicable when $X_3 > X_2$. As the number of production runs increase, the waiting increases because the stations will be occupied more. <u>Further research is needed for computing the WT_{factor} rather than the empirical estimate used here</u>.

<u>**Batching Effect on TF using Factory Physics Perspective**</u> - If a station is waiting for many batches from the previous station (the stations are unbalanced with respect to processing capacity; the previous station's processing capacity is significantly smaller than this station), before processing, there is an added idle time for the second station waiting for all the batches to come through to it. The process area immediately after the area with capacity restriction will start processing only after all the batches in the previous area are finished. As a result, a batch waiting time (TWT Equation 2.18) is to be added. Hence the computation which captures the total time (TF_{ideal}) is written as given in Equation 3.16. Here the term $X_{2a} \cdot t_a$ in Equation 3.15 is updated as $((X_{2a} - 1) / 2u_j) \cdot t_a$. The difference between Equations 3.15

(TF_i) and 3.16 (TF_{ideal}) is that the latter takes utilization of the station where batching occurs whereas the former does not.

$$TF_{ideal} = t_{on} + \left[t_{sa} + X_3 \cdot \left(\frac{X_{2a}-1}{2\,u_j} \cdot t_a \ + t_a\right) + t_{ca}\right] + \sum_{\substack{j=1\\ j\neq a\\ j\neq b\\ a\neq b}}^{m}\left[(t_{sj} + t_j + t_{cj})\right] + \left[t_{sb} + \left(\frac{Y}{X_3} \ \cdot t_b\right) + t_{cb}\right] + \ t_{off} \ + WT_{factor} \quad \text{; where } a\,,b \ \in(1,m\,) \qquad 3.16$$

The TF equation developed is improved by introducing variation and disruption effects to resemble more to the real-world system.

<u>Variation Effects</u> - The time to finish for systems with variability (TFV), could be found by applying Kingman's equation [3],[70] (V·U·T) to the equation for TF developed earlier (TFideal), and is given by Equation 3.17. The coefficient of variation of arrival (ca) at the second station onward is computed considering the propagation of variation effects given in Equation 2.17. The coefficient of variation of the process (ce) for each station is computed using Equation 2.9 inputting the corresponding values of the variables for that station.

$$TF_V = t_{on} + \left[t_{sa} + \frac{(c_{aa}^2+c_{ea}^2)}{2} \cdot \frac{u_a}{1-u_a} \cdot t_a + \ \left(\frac{X_{2a}-1}{2\,u_j} \cdot t_a \ + t_a\right) \cdot X_3 + t_{ca} \right] + \sum_{\substack{j=1\\ j\neq a\\ j\neq b\\ a\neq b}}^{m} \left[t_{sj} + \frac{(c_{aj}^2+c_{ej}^2)}{2} \cdot \frac{u_j}{1-u_j} \cdot t_j + \ t_j \ + t_{cj}\right] + \ \left[t_{sb} + \frac{(c_{ab}^2+c_{eb}^2)}{2} \cdot \frac{u_b}{1-u_b} \cdot \left(\frac{Y}{X_3} \ \cdot t_b\right) \ + \ \left(\frac{Y}{X_3} \ \cdot t_b\right) + t_{cb} \right] + \ t_{off} \ \ + WT_{factor} \quad \text{; Where } a,b \ \in (1,m) \qquad 3.17$$

<u>The first factor in the equation for every station is the representation of variation by using the famous Kingman's equation followed by the processing time at</u>

that station. For the station with subscript ‘a’ the second term represents the transfer wait time for the batches and also the total processing time at that station.

Disruption Effects - The effect of disruption can be incorporated by changing the time in the equations as: (t_j/A). The time to finish with disruption effects is effectively bringing in the value of availability for TF. It should be noted that the resources have an effect of a series network. If all the four critical resources (equipment, material, people, and schedule or information) [6] are needed, all of them should be available. Hence the availability of all the resources combined together is computed by $A = A_E \cdot A_M \cdot A_P \cdot A_S$, which is based on the reliability concept of series systems. If any resource is not needed, set its corresponding value to one. As an example, in a fully automated system, people are not needed for the operations to be performed and as such its availability is determined by A = AE · AM · AS. More information about this is in Section 3.6. The time to finish for a system with no variation but with disruptions (TFD) is computed in Equation 3.18.

$$TF_D = t_{on} + \left[t_{sa} + \left(X_3 \cdot \left(\frac{X_{2a}-1}{2\,u_j} \cdot \frac{t_a}{A} + \frac{t_a}{A}\right)\right) + t_{ca}\right] + \sum_{\substack{j=1 \\ j\neq a \\ j\neq b \\ a\neq b}}^{m} \left(t_{sj} + \frac{t_j}{A} + t_{cj}\right) + \qquad 3.18$$

$$\left[t_{sb} + \left(\frac{Y}{X_3} \cdot \frac{t_b}{A}\right) + t_{cb}\right] + t_{off} + WT_{factor} \text{ ; Where } a, b \in (1, m)$$

Variation and Disruption Effects Combined - In practice, systems will exhibit the effects of variation and disruption at the same time. If a system expects both variation and disruptions with appropriate flow designed (indicated by the values of X_1, X_2 and X_3), then the TFVD can be computed as shown in Equation 3.19 which is obtained by combining Equations 3.17 and 3.18.

$$TF_{VD} = t_{on} + \left[t_{sa} + \frac{(c_{aa}^2 + c_{ea}^2)}{2} \cdot \frac{u_a}{1-u_a} \cdot \left(\frac{t_a}{A}\right) + \left(\frac{X_{2a}-1}{2\,u_j} \cdot \frac{t_a}{A} + \frac{t_a}{A}\right) \cdot X_3 + t_{ca}\right] + \sum_{\substack{j=1 \\ j \neq a \\ j \neq b \\ a \neq b}}^{m} \left[t_{sj} + \frac{(c_{aj}^2 + c_{ej}^2)}{2} \cdot \frac{u_j}{1-u_j} \cdot \left(\frac{t_j}{A}\right) + \left(\frac{t_j}{A}\right) + t_{cj}\right] + \left[t_{sb} + \frac{(c_{ab}^2 + c_{eb}^2)}{2} \cdot \frac{u_b}{1-u_b} \cdot \left(\frac{Y}{X_3} \cdot \frac{t_b}{A}\right) + \left(\frac{Y}{X_3} \cdot \frac{t_b}{A}\right) + t_{cb}\right] + t_{off} + WT_{factor} \quad ;\text{Where } a, b \in (1, m) \qquad 3.19$$

When there is no variation or disruption, the coefficient of variation in the above equation will be zero; the availability will be one. As a result, the above Equation 3.19 modified will represent the ideal condition as given in Equation 3.16.

3.2.2.3 Parameter Values for Designing

It is very important to be aware that the real parameter values will not be known when the system is designed. For example, the coefficient of variation of the arrival or the process is not available because the facilities have not started production. Similarly, the availability of the resources is also not available. Therefore, expected values for these parameters (either from prior knowledge or from similar industries) are to be given to the designer in order to facilitate the design. Within the given parameter values, the system should function, and all the manufacturing activities will have to be completed within the time constraints.

The equations developed for TF are used in the algorithms and computations with the parameter values given. The different phases of the framework in Section 3.1 are detailed and explained in Sections 3.3 to 3.8. The algorithms are explained in Chapter 4.

3.3 Phase 1 – Capacity Based on TF in Ideal Conditions

The objective of this phase is to check the existing capacity of the system using time to finish in ideal conditions (TF_i) and time available (TA). The inputs are derived from the information available about the product, process, demand, facility capabilities/restrictions and the TA. A few examples of the type of <u>inputs</u> are the processing capacity of the stations, the type of processing (batch or single piece processing) and processing time at each station. Capacity is traditionally defined as the maximum quantity that can be produced in a unit of time; it is the product of time (operational time minus time lost due to breakdowns or set up changes) and yield per unit of time.

This model looks at the <u>time to finish (TF)</u> and the time available (TA) to make a determination about the capacity (Section 1.6). There are three conditions by which capacity is categorized in this model. (1) If the current capacity is greater than demand by a threshold (TF << TA), then the system will not be redesigned. (2) If the current capacity is greater than demand (TF ≤ TA) but in the threshold, then the system will require improvements. (3) If the existing capacity is not sufficient (TF > TA), then ways to enhance the capacity are analyzed by the concepts of 'ReLeanability' (reliability of lean systems [63], [64], [65], [66], [67], [68]) developed by CASRE [69] at the University of Tennessee (UT). The 'ReLeanability' model transforms productivity based on stabilizing the system before designing the flow. This concept is unique in the Operational Excellence models. The result is a precise surgical, yet fundamental approach to enhance capacity. TF will be indicative of the capacity of the system; if the TF is less than the time available, there is sufficient capacity to meet the demand.

The threshold of operational time is to be established here; if the time to finish is exactly equal to the time available, then, theoretically, it may be feasible, but in practice the design is not sustainable. Once the threshold is established, the capacity is checked again with respect to the TF so that there is sufficient gap considered to account for other factors that may come up which are not considered while designing the system. The time buffer or the threshold could be established by looking at the department of labor laws for factory operation at the federal level (Fair Labor Standards Act (FLSA) [70]) and at the state level. Different states have varying break/rest laws as found in [71] – [74]. There are organizations which provide more rest/break periods than stipulated by law; for example, a company may provide 10-minute breaks every two hours in addition to a lunch break. Using the law as the lower point for estimating the time buffer, a range of 8.33% to 15% could be used. **If the operations are continuous in nature, especially if the operations cannot be stopped once it is started, the production line does not stop and hence the time buffer may not matter.** As a result, a threshold of 85%, 90%, 95% or 100% can be used for the manufacturing operations depending on the type of manufacturing operations and the location of the plant. With respect to capacity utilization historically a maximum of 90% was achieved in the late 1960s to early 1970s [18].

The computation of TF and the development of the equations were discussed in Section 3.3. In this phase, the time to finish in ideal conditions (TF_i) is computed.

Formulation: An initial estimate of the TF_i will be made here using Equation 3.15; the variables used are t_j, X_3, X_{2j} and Y. An example is provided in Appendix A.

3.4 Phase 2 – Strategy to Enhance Capacity based on TF

The objectives of this phase are to: (1) identify the critical path, (2) classify the critical path, (3) compute utilization of stations, (4) identify the bottleneck station(s), and (5) recompute the ideal conditions of TF in ideal conditions, using utilization of stations as a new variable. The inputs to this phase are all the variables used in phase 1 (such as, the processing capacity of the stations, the type of processing (batch or single piece processing) and processing time at each station. In addition, the network diagram of the processes is another input.

This phase starts by defining the strategy to enhance capacity based on TF. The strategy is to identify the critical path and concentrating on that path initially so that the activities in the critical path are designed properly. If there are many paths, the paths are to be ordered based on their criticality (by using Critical Path Method). By using the network diagram of the processes and the activity times at each process, the duration of each path is calculated. The path with the longest duration is the critical path. This dissertation assumes that there will not be two paths which have the same duration. The subsequent paths are considered, and focus is given to them in the order of their criticality. The classification of the system (critical path) is explained in Section 3.4.1.

The utilizations of the stations are computed to identify the bottleneck. In literature, the utilization of a station is computed as the ratio of the arrival rate (r_a) to the processing rate (r_e) [3]. The average production per a unit time for every station in the line is computed and compared; the station with the lowest production will be the bottleneck as proposed by the Theory of Constraints [74]. The throughput of the line will be determined by the capacity of this bottleneck and hence the capacity of the system will be the output of this station in any given time period. The **bottleneck station can also be identified by the utilization of the stations**. Since this model is focused on time, utilization is represented and computed as the ratio of 'time a station is used' in the transformation processes to the 'time allocated'. Utilization of all the stations is computed with the time ratio; the station with the highest utilization is the bottleneck in the path (line). **When there is more than one product in the manufacturing mix, the bottleneck may be a floating one (the bottleneck stations may change depending on the products in the assembly line)**. This is fundamentally different from the idea of a single entity being the bottleneck in the system [75], [74]. Over a long period of time the bottleneck may be a single station, but when the time frame under consideration is short, bottlenecks may be of the floating type. **Floating bottlenecks** [2], [76] normally occur only when different products are manufactured; in the case of a single product manufacturing bottleneck, it is normally a particular station. It is important to understand the critical path and the bottleneck stations in the line irrespective of the type of system classification.

The time to finish is recomputed using Equation 3.16 (TF_{ideal}); the time to finish computed in phase 1 (TF_i Equation 3.15) does not use utilization as a variable in the equation. All the variables used in phase 1 such as the processing time at each station (t_j), the number of production runs (X_3), the number of batches per run (X_2), and the demand are used here; in addition another variable for the utilization of the station where batching is needed is used. This dissertation has the requirement that the demand should be met (as given in Chapter 1, TH is set equal to demand) and hence the capacity should be in existence; by checking whether the TF_{ideal} is less than TA, the capacity is verified. The outputs of this phase are the critical path, utilization of the stations, bottleneck station, the TF_{ideal} using station utilization as a variable and the classification of the system based on the critical path.

3.4.1 Process Characteristics and System Classification

After the critical path is identified, the system is to be classified based on process characteristics. Depending on how the system is classified, the approach takes one of three paths: (1) Variation, Disruption and Flow Design; (2) Disruption, Variation and Flow Design; (3) Flow Design followed by variation/disruption. The improvement strategy is dependent on the system classification. The order of design of operational excellence depends on the classification of the system and the process characteristics. These are captured in Table 2. Systems with variations and disruptions are to be studied carefully in order to stabilize them.

The process characteristic of any system will fall into any of these three classifications: “deterministic”, “stochastic” or “Bayesian” [2], [77]. “A deterministic system is one in which no randomness is involved in the development of future states of the system. In the case of such a system, arrival, flow and process time are predetermined. Only fully automated systems are 100% deterministic. For stochastic systems, the processes will have repeatable process steps but have variation in process time and logical movements; the process time will be stochastic while arrival and flow are predetermined. The processes of a Bayesian system are conditioned by the probability of taking different paths across several steps. Bayesian systems will have stochastic process time whereas the arrival and the flow will be probabilistic" [2]. Most manufacturing processes are not Bayesian because the flow is known and is predetermined. In service organizations, the processes are Bayesian. The order of importance of the factors (priority) for the above-mentioned systems as shown in Table 2 are indicated by the numbers 1, 2 and 3; with 1 being the most important [2].

When designing systems, a discussion is to be carried out about the manufacturing operations of the system to determine whether or not the processes are well established or whether or not any change in the operations are possible, if the processes are considered highly variable or major disruptions are anticipated. In such cases, the sources and causes of process variations or disruptions are to be studied carefully so that the root causes can be mitigated before looking at establishing the operational manufacturing system. By identifying the root causes and taking corrective actions, the processes are stabilized. By reducing variations and disruptions, the TF can be reduced. This dissertation assumes that the processes are

Table 2 Systems Classification and the Order [2]

System Type	Flow	Variation	Disruption	Action
Deterministic	3	2	1	Stabilize through Reliability Concept and then design flow
Stochastic	3	1	2	
Bayesian	1	2	3	Design Flow, then variation or disruption

designed, stable and cannot be changed; the operational aspects can be changed. The layout cannot be changed.

Since this research focuses on manufacturing, the discussion starts on deterministic and stochastic systems followed by the flow design. Only batching and balancing (if possible) issues are covered for the flow design for this dissertation. The algorithms (critical path, bottleneck, floating bottlenecks and system classification) are explained in Section 4.1 with examples. The methodology follows the order obtained as the result of classification of the type of system (critical path). The system classification depends on the process characteristics; most manufacturing systems are not fully automated (no manual intervention needed) and hence the system is considered as stochastic, therefore the variation effects are considered in the next phase (phase 3).

3.5 Phase 3 – Variation

The objective of phase 3 is to consider variation issues, its impact on time and hence capacity. The inputs to this phase are all the variables (X_{2j}, X_3, t_j) and its values, as well as the utilization of stations (u_j) computed from phase2. The theory associated with the effect of variation on cycle time was discussed in Section 2.6. There is no discussion on the time to finish (which is the main subject of interest of this dissertation) in the literature.

The general blocks in variation analysis/studies are shown in Figure 3.3. The critical path and the bottleneck are identified and the system is classified in phase 2 if the system classification is stochastic; a determination is made about the balance of the line and the utilization of stations is available (computed in phase 2). The sources of variation (critical resources) are to be identified and arranged in the order of prominence. The utilization of the stations computed in phase 2 is used to decide whether the variation in process or arrival is to be focused on at a station.

The design analysis should concentrate first on whether the line is balanced or unbalanced using the logic shown in Figure 3.4 whose notations are given in Table 3. The Mean Absolute Error Cycle Time Overall (MAECTo) is the average of the absolute value of the difference between the mean processing time (cycle time) of the stations and the average across all the stations in the line. The Root Mean Square Error Cycle Time Overall (RMSECTo) is the RMSE of the difference between

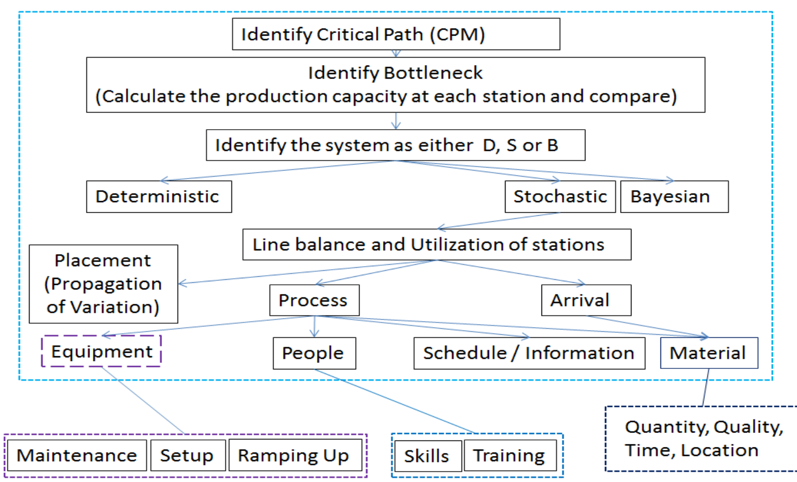


Figure 3.3 Variations General Blocks

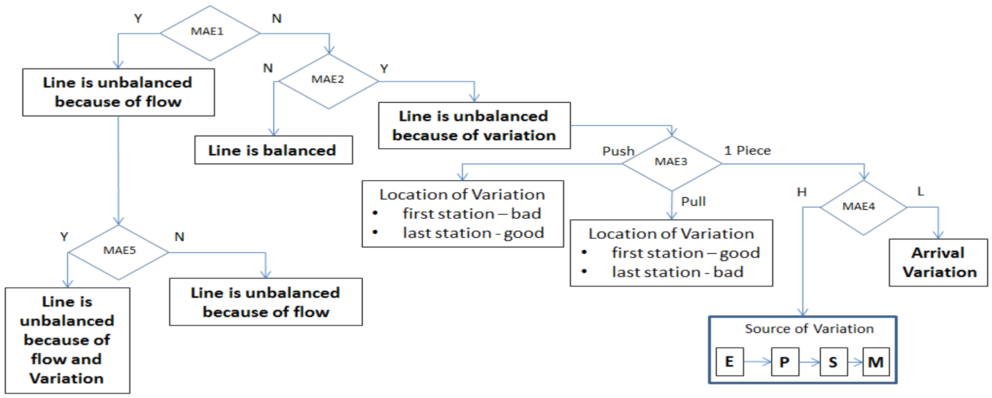


Figure 3.4 Mean Absolute Error Comparison Logic

Table 3 Mean Absolute Error Comparison Logic Notations

Notation	Decision Questions
MAE1	Is the Mean Absolute CT Error overall (MAECTo) large? Is the Root Mean Square Error Cycle Time Overall (RMSECTo) large?
MAE2	Is the CV overall (CVo) large for the balanced line?
MAE3	Is the system one- piece flow / Push / Pull?
MAE4	Is the utilization high or low?
MAE5	Is the CV overall (CVo) large for the unbalanced line?

the average processing time (cycle time) of the stations and the average across all the stations in the line. The Coefficient of Variation Overall (CVo) is the coefficient of variation across all the stations in the line, not just one station. This is obtained by the values used for the MAECTo. If the values of MAECTo or RMSECTo are not low, then the line is unbalanced. If the CVo is large (>0.75), then variation plays an important part in causing the unbalance of the line.

An example for this analysis with an average processing time of the four stations as 17, 14, 45 and 109 units of time, respectively, shows that the MAECTo is 31.375, the CVo is 1.42 and the RMSECTo is 53.68. The average of the processing time, across the four stations, is 46.25 and the standard deviation is 56.65. This leads to the decision that the line is unbalanced because of both variation and flow (both MAECTo and RMSECTo are high).

The formulation for the time to finish with variation effects (TFv) were detailed in Section 3.2.2 leading to the Equation 3.17 (this equation can represent real processes with multiple variables). The important variables are: c_{aj}, c_{ej},u_j, t_j, X_3, X_{2j} and the information about inventory buffer capacity (to determine WT_{factor}). There are two steps of computation needed before the TF_V is calculated: - Step 1- c_{ej} is obtained by equation 2.9; the variables for this are: c_{oj}, A, m_r, t_j, (c_{rj}). Step 2 - coefficient of variation of arrival at the second station onwards was obtained by applying Equation 2.17; the variables (the values of which are from the previous station) are: u_{j-1}, c_{ej-1} and c_{aj-1}. The equation for TF_V is nested with two other equations (equation for c_e and for c_a) in each station. The algorithms for phase 3 are discussed in detail in Section 4.2.

3.6 Phase 4 - Disruptions

The objective of phase 4 is to consider disruption issues, its impact on time and hence capacity. The inputs to this phase are all the variables (such as X_{2j}, X_3, u_j, t_j, Y) and its values are passed on from phase 3. The theory associated with the effect of disruption on cycle time was discussed in Section 2.6 (variation and disruption are connected by the availability factor). The availability factor is recomputed in this phase. There is no discussion on the time to finish (which is the main subject of interest of this dissertation) in the literature.

Analysis of disruption issues starts by identifying line and yield issues. Setup changes and downtime causes disruptions; by identifying and classifying actions related to set up changes as internal or external and then trying to do all possible external activities when the line is running reduces disruptions. Also, implementing a planned maintenance policy reduces disruptions (downtime) compared to a run to failure policy. The availability of the total system is computed based on the critical resources.

A manufacturing system is a network of processes that is goal-oriented and through which parts flow. Disruption to any of the critical resource (CR) will affect the performance of the system. The tree structure of the CRs and the variables and its subcomponents (which are used to develop the algorithm) are shown in Figure 3.5. Some of the important variables to be considered for the materials are: (1) the total quantity, (2) availability, (3) sources of materials, (4) number of batches and sub-batches, and (5) schedule and quantity needed in each delivery.

Some of the important variables to be considered for the equipment/machines are the (1) number of machines (if needed), (2) capacity of machines, (3) availability and (4) reliability. When designing systems, attention is given to the practical capacity (PC) of machines rather than the theoretical capacity (TC). The availability of machines is very important in successful operations. Reliability has an impact on the availability. If the machine is not reliable, then it may not be available. Therefore, in any manufacturing operation the machines' reliability is very important. If the operation is sequential, the non-availability of a machine, when it is needed, will

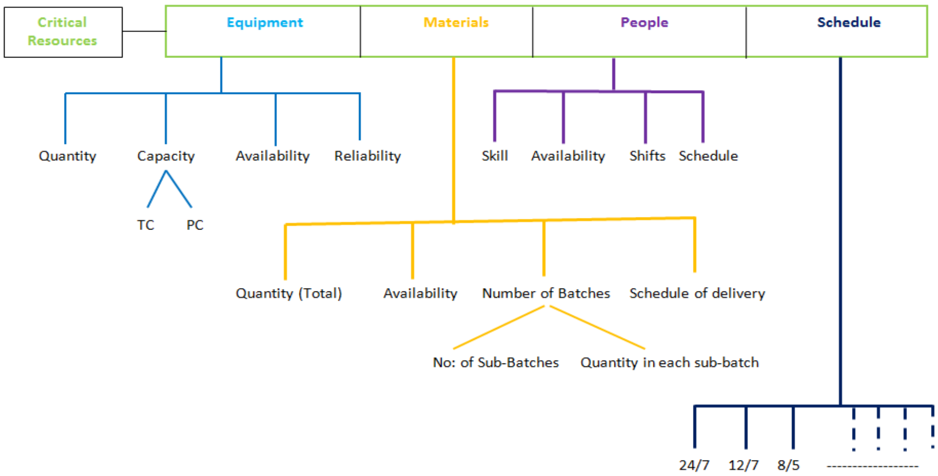


Figure 3.5 Tree structures of the critical resources

affect the downstream operations as well. Proper maintenance of machines makes them available, especially in operations when it is not in continuous use. People are another important component of the system. The important variables, when it comes to people, are (1) skill, (2) availability, (3) shifts, and (4) schedule. The material

quantity and schedule are to be aligned with the capacity and the operational schedule of the stations. Some of the ways the operations can be scheduled are: (1) 24/7, (2) Two 12 hour/7, (3) day operations only, (4) Monday through Friday only. The list is not comprehensive. In this approach it is assumed that the other important resources, such as building(s) and money for capital and operating expenses, are available. The design starts from the final product and is worked backwards through each stage of manufacturing until it reaches the supplier of the main raw material(s).

It is of paramount importance to clearly identify disruptions and develop frameworks to anticipate and control. In Lean Enterprise Systems, disruption is anything that hinders the continuous flow of a system. Since disruptions are inevitable (but can be minimized), frequent disruptions, with small downtimes, are preferred to infrequent disruptions that have significant downtimes. Disruptions to the bottleneck machine/equipment will have an increased negative impact on manufacturing than others. Disruptions can be avoided by ensuring reliable resources everywhere at all times in the process; but this is not practical. Reliability of a machine is dependent on its availability (A). Mean Time to Failure (MTTF (m_f or t_f)) and Mean Time to Repair (MTTR (m_r or t_r)) determines availability as shown in Equation 3.20 [3].

$$A = \frac{MTTF}{MTTF + MTTR} \qquad 3.20$$

One way to minimize the effects of disruptions is to make sure that the resources are available when needed. If the reliability of the components of the system is very high, then disruptions will be minimal. Hence the focus should be on providing stations with a very high reliability factor. There should be a cost benefit analysis carried out because machines with very high reliability may be costlier. Some of the issues connected to disruptions could be rectified by having a proper schedule for both operations and maintenance.

If all the processes are in series, then the total reliability of system will be much less than the reliability of one process. If there are n processes (stations) which have a reliability factor of r_1, r_2, r_3… r_n then the total reliability of the system (r_s) is given by Equation 3.21. If $r_1 = r_2 = r_3 = \ldots r_n = r$, then it can be written as in Equation

3.22. The system will fail if one component fails; $r_1 = r_2 = r_3 = \ldots\ldots r_n$ is also the probability that the machines are operational when it is needed.

$$r_s = r_1 \cdot r_2 \cdot r_3 \cdot \ldots \cdot r_n \qquad 3.21$$

$$r_s = r^n \qquad 3.22$$

Systems with parallel stations will be more reliable than a system without parallel stations. If all the stations are in parallel, then the total reliability of the system r_p is as given in Equation 3.23. If $r_1 = r_2 = r_3 = \ldots\ldots r_n = r$, then it can be represented as in Equation 3.24.

$$r_p = 1 - (1 - r_1) \cdot (1 - r_2) \cdot (1 - r_3) \cdot \ldots \cdot (1 - r_n) \qquad 3.23$$

$$r_p = 1 - (1 - r)^n \qquad 3.24$$

Series parallel combinations will be helpful if one or a few of the stations has a lower reliability than others. In this case, the reliability of the system can be improved by adding machines in parallel where needed. Addition of machines depends on whether or not it is physically possible and on the cost of the machines. If there are any sub processes for any of the processes, then the reliability of each subcomponent is to be considered when the reliability of the stations and the reliability of the system are computed. The reliability equations could be incorporated (this dissertation assumes that equipment cannot be added or changed) in the algorithm shown in Figure A.14; it could be used in the algorithm in Figure A.12 for cost benefit analysis.

The concept of reliability is used for computing the availability of the system. For each station the individual components are identified and the station availability is computed, which leads to the availability to the entire system (for the resource equipment) considering all the stations in the system. The availability of all other resources is computed (if possible) or assumed based on the opinion of the subject matter experts. The entire system availability is derived as a series combination of the four critical resources (if all of them are needed); hence the availability is $A = A_E \cdot A_M \cdot A_P \cdot A_S$. The general blocks in disruption studies are shown in Figure 3.6. Disruptions connected to the sources (four critical resources [6]) are to be studied carefully when designing any system. The formulation of TFD, given in Equation 3.18, is used for the computation. The availability factors, updated in the algorithms, are used in the final computation. The variables already defined in phases 1 to 3 are used here. The algorithms for this phase are discussed in detail in Section 4.3.

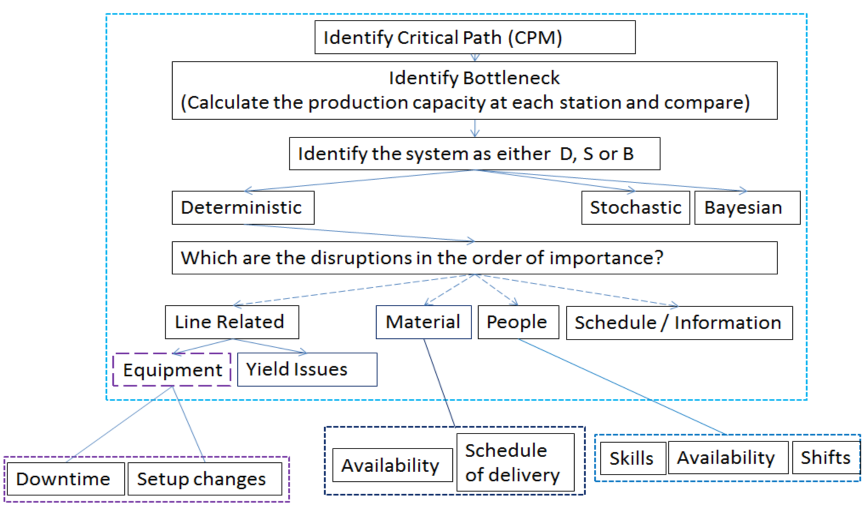


Figure 3.6 Disruptions General Blocks

3.7 Phase 5 - Flow Design

The objective of this phase is to design flow that is appropriate for the product keeping facility restrictions in consideration. The inputs to the system are the variables and its values used in the previous phases. Flow is generally designed/ controlled in the manufacturing process. Flow is dependent on WIP, process time, batch size and the balance between the stations in the manufacturing operations. In designing flow (which is one of the five principles of Lean), the goal is to have a single piece flow under balanced conditions (without disruptions) according to the lean manufacturing approach [78]. Ideal flow is not a possible goal if the production line cannot be changed or modified and if the line is unbalanced, because of both processing time unbalance and capacity balance at the stations which cannot be fixed (especially when the system does not allow WIP buffering).

The main block diagram for the flow design of the manufacturing system is shown in Figure 3.7. The main components are Flow Planning, Flow Prerequisites and Advanced Flow Design. The detailed block diagrams for the individual components in the main block diagram of Design for Flow is given in Appendix A. This dissertation focuses on batching decision only. Balance design may require facility layout changes and/or inventory level changes. If neither are permitted, the line will remain unbalanced. This dissertation only looks into the determination of the batch size (X_1), number of batches per run (X_2) and the number of production runs (X_3) needed to finish manufacturing of the entire quantity demanded. These are computed at the start in the formulation of variation and disruption; TF for variation

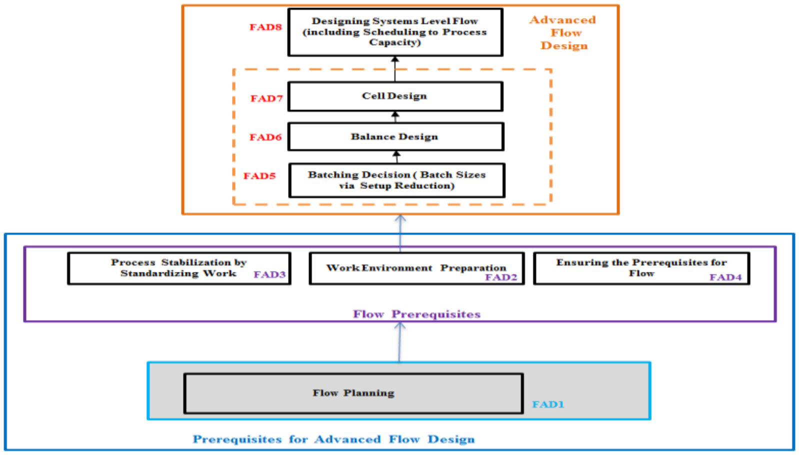


Figure 3.7 Blocks in the Design for Flow [2] (FAD)

and disruption uses the variables X_2 and X_3. The algorithms are explained in Section 4.4.

3.8 Phase 6 – Output of the Model – System Design

The TF in different conditions (ideal and practical) with the appropriate batch size, the number of production runs and the number of batches per run, will be the output of this model for the manufacturer whose facility is time limited. This TF will ensure that the throughput will meet the demand. This output will form the basis to make the manufacturing decisions by the organization. There would be many combinations which will satisfy the time constraint. One of the combinations is to be selected by the decision makers, which will form the basis for other manufacturers in the chain so that their production follows the requirement from the facility with time constraints. The time required by the other manufacturers in the chain is estimated and the total time to complete the manufacturing across the chain can be computed.

3.9 Summary of Phases 3 - 6

By concentrating on the areas where variations and disruptions occur, the processes can be stabilized. If the repair variation can be minimized and controlled, it will improve the process at that station which will in turn reduce the variability resulting in better throughput time. If a maintenance policy is implemented to service the equipment/stations rather than waiting for a run to failure approach, it will significantly reduce the breakdowns and hence the repair variability and in turn, the variability of the process will be improved. Planned maintenance will also result in a better mean time to repair which will increase the availability. If there are set up changes involved in the manufacturing process, identifying the activities as interval vs external and trying to change as many as possible to external activities, will reduce the time when the machine/ line is to be stopped to change the set ups. If new machines are introduced (which is out of scope for this dissertation), quality and utility of the machine for the process is to be given thorough consideration. Hiring and maintaining properly skilled people through appropriate training/re-training will reduce variations and disruptions caused because of human error. Identifying and getting the right material at the right time to the right place in the required quantity of the right quality at the scheduled time, will take away many of the issues related to material variations/disruptions. Providing the correct information to all those involved in this transformation process and having a perfectly aligned schedule with all the resources ensures that the process will function the way they were designed.

Using the appropriate equation developed, the TF is calculated. The total time required for the production through all the manufacturers is also calculated. The possible combinations where TF <TA, for the facility with time restrictions, forms the basis for the management to make a decision. The selected combination will have to be used as the input for other manufacturers in the chain to plan their operations.

3.10 TF, Schedule and the Time of all Manufacturers in the Chain

The computed time to finish assumes that the facility of the manufacturer ($Mfgr._n$) operates 24/7. It can be modified to include different scheduling options. For example, if the facility operates only 8 hours a day, then the time (TF) will be at least 3 times of what is computed. Or if it operates 12 hours a day, then the time (TF) will be at least 2 times and so forth. The factor will be decided by the ratio of 24*7 = 168 hours to the total time scheduled in a week in hours.

The effect of increasing the number of machines could be studied by considering the addition of process areas in parallel to the existing ones, wherever capacity is restricted. The effect of adding each machine will be that the capacity will be increased with the same proportion as the number of machines. If two process areas are available, the capacity will be doubled; if three process areas are available, the capacity will be tripled and so on. When the number of machines is increased, the TF will come down, which in turn will have the effect of having more options to manufacture the product compared to the options selected without addition of extra machines. An important factor to be considered here is the cost of adding machines and getting them installed. In some cases, there will be regulatory restrictions in place which will prohibit adding more machines.

3.10.1 Comparison of all the Combinations for Feasibility

Now that the total time and the capacity are computed, the next step is to select the feasible combinations which will satisfy all the constraints defined. The time to finish (TF) computed will be checked with the time available (TA) and the options which get finished within the available time will be selected (TF ≤ TA).

3.10.2 Schedule

The schedule for the materials follows the variables X_1, X_2, and X_3. Scheduling of the process areas also follows the sequence of material flow. It is to be ensured that the machines in process areas are ready by the time material arrives at that area. Any maintenance or complicated set ups are to be finished before the arrival of the materials in that area. Scheduling of people follows the material flow sequence and the scheduling of machines. If specialized maintenance/set up personnel is required, they should be made available before the time the manufacturing operation commences.

3.10.3 Computing the Total Time for all Manufacturers

Once the time for the manufacturing operations to be completed for each manufacturer is computed, the total time to manufacture the product through its manufacturing chain is calculated. Only the time spent inside the manufacturing operations, once the process starts until it is finished, is considered. The product from each manufacturer may be kept in storage before the operations of the downstream manufacturer starts. Such time is not considered as part of this research.

3.10.4 Manufacturers in the Chain

If there is a time limit constraint on the availability on the other manufacturers in the chain, computing the TF for each such manufacturer is replicated and compared with the corresponding TA. The capacity of each manufacturer is computed considering the processing capacity of each process area and checked to decide whether the manufacturer can meet the demand with the existing infrastructure. If existing capacity cannot meet the demand during the specified production time, then capacity addition (not by making physical changes) is required before designing the manufacturing system. Select the options that satisfy the constraints and continue to the next manufacturer.

4
ALGORITHMS

This chapter discusses the algorithms for phases 2 to 5 that were developed for this dissertation. The algorithms are based on the methodology developed in Chapter 3 Sections 3.4 to 3.7; the flowcharts for each algorithm are given in Appendix A with corresponding references.

4.1 Phase 2 Algorithms for Strategy

Knowing the process characteristics is one of the essential steps for conducting operational manufacturing system design. . The algorithm (Figure 4.1) is designed in such a way that it can classify the system/process by finding out the answers to a set of questions provided in Table 4 . This will lead to the system under consideration being classified as “Bayesian”, “Deterministic” or “Stochastic” [2]. The definition and descriptions (Section 3.4.1) of the above terms are to be given to the person(s) making the decisions about operational system design. This helps to gather the information needed as the input values to the classification algorithm. The developed algorithm helps in the determination of the critical path (using Critical Path Method - CPM) and the bottleneck. It also branches out to the appropriate type of

Table 4 System Classification

Notation	Description
SCG1	Is the Critical Path known?
SCG2	Is the design concentrating first on the critical path?
SCG3	Is the production capacity or utilization of each station known?
SCG4	Is there a station in the line which is bottleneck?
SCG_{time}	Is the ideal conditions (TFideal) known?
SCG5	Is the system classified as Bayesian?
SCG6	Is the system operations Deterministic in nature?

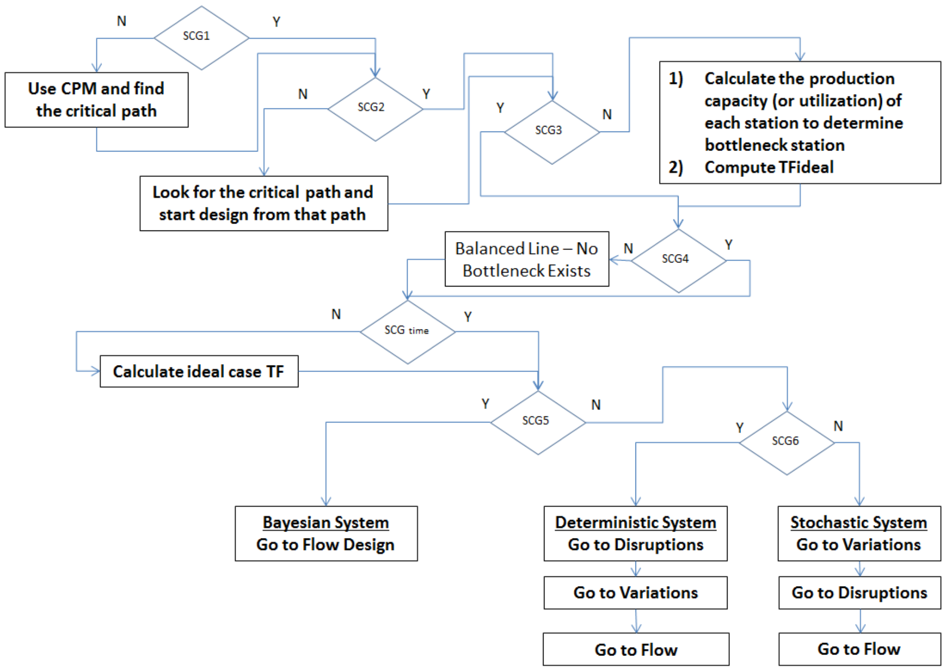


Figure 4.1 Phase 2 Algorithm Flowchart

system based on the input values fed. In a multi-product manufacturing environment, the bottleneck may not be a single station, which will result in floating bottlenecks.

An example of floating bottlenecks (Section 3.4) is briefly described here. Assume that there are three products to be manufactured and their processing times at the corresponding station are given by in Table 5 . If the products are always made in the same sequence, the products will be at the stations with their corresponding processing times as shown in Table 6; the cells of which denotes product, process time for the product at the stations. When all the stations are occupied, the bottleneck floats between stn1, stn2 and stn4.

The pseudocode for this floating bottleneck example is given in Figure 4.2; j represents the station (j = 1 to J), k (k = 1 to K) the row index and tj is the processing time in station j. The pseudocode is written assuming that the data file for Table 6

Table 5 Products and Stations

Product	Processing Time			
	Stn1	Stn2	Stn3	Stn4
A	6	8	2	5
B	5	6	4	9
C	3	5	8	6

Table 6 Production Sequence and Corresponding Products

Sequence	Processing Time			
	Stn1	Stn2	Stn3	Stn4
1	A, 6			
2	B, 5	A, 8		
3	C, 3	B, 6	A,2	
4	A, 6	C, 5	B, 4	A, 5
5	B, 5	A, 8	C, 8	B, 9
6	C, 3	B, 6	A, 2	C, 6
7	A, 6	C, 5	B, 4	A, 5
8	B, 5	A, 8	C, 8	B, 9
9	C, 3	B, 6	A, 2	C, 6
10	A, 6	C, 5	B, 4	A, 5
11	B, 5	A, 8	C, 8	B, 9
12	C, 3	B, 6	A, 2	C, 6
13		C, 5	B, 7	A, 5
14			C, 8	B, 9
15				C, 6

```
For k = 1 to K
        Find jmax = argmaxj (tj)
        If jmax = 1, index 1 = index1 + 1
        Else if jmax = 2, index2 = index2 + 1
        Else if jmax = 3, index3 = index3 +1
        Else index4 = index4 +1
        BTLtotal = index1 + index2 + index3 + index4
End
Pr1 = Index1/K; Pr2 = index2/K; Pr3 = index3/K and Pr4 = index4/K
```

Figure 4.2 Floating Bottlenecks Formulation are populated. The data used will be focusing on the rows where all the stations are loaded (rows 4 to 12). The flowchart of this algorithm is shown in Figure A.1, which is implemented in MATLAB (with the values excluding the product and substituting ‘0’ for cells without values are loaded in an excel file) as given in Appendix C – Sample MATLAB Codes and GUI. The probabilities are 0.25, 0.25, 0.0 and 0.5 for stations 1 to 4 respectively to become the bottleneck when the algorithm is run with the values of Table 6 applied.

Floating bottlenecks will not have much effect on TF, (the reason being the use of utilization of stations as a variable in the equation for TF), if the sequence of products is already determined. Manufacturing planning will ensure that the sequence is developed. Once the product sequence and the processing time of each product at each station is known, the time each station is occupied in production activities is computed. Each station time will be a summation of the manufacturing time at that station for all the products. This dissertation focuses on a single product and hence the computations reflect only a single product.

4.2 Phase 3 Algorithms for Variation Design

In this subsection, the algorithms for variation studies are given. The logical questions to develop the algorithm for the system design to withstand variation are given in Table 7. These algorithms are based on the methodology discussed in Section 3.5. The notations are used in the decision boxes in the flowcharts. **Any improvements in the system will bring down the coefficient of variation (for**

example, providing training will improve the skills of the people reducing the variation caused by them) which in turn will reduce the TF.

These are converted into algorithms as shown in the flow charts from Figure A.2 to Figure A.9 in Appendix A. The algorithm in Figure A.2, corresponding to the submodule 'Process Control', determines whether the operations are process-dependent or arrival-dependent based on the utilization of the stations. For each station, its utilization is computed based on the total time it is used in the allocated time. Utilization is computed in literature [3] as the ratio of the arrival rate to the average production rate at each station as given in Equation 2.3. Since this model is concentrating on time, utilization represented as the ratio of time a station is used to, the time allocated is appropriate. Utilization for all the stations in the line is already computed in the system classification algorithm in Section 4.1. If the utilization is high, then the operations are process dependent. If it is arrival-dependent, the issues related to arrival variation are considered before studying the process variation and vice versa. The other factors in this algorithm are binary (Y/N or H/L), the value of which leads to the path the logic takes. The MATLAB code for this algorithm is given in Appendix C.

Table 7 Notations of Design for Variation

Sub Module	Notation used in the Flow chart	Decision Rule / Condition
Process Control	VG12	Is the utilization of stations known?
	VG14	Is there any variation either in arrival or in process?
	V6	Are the arrival variation and process variation same?
	V7	What is the utilization of the station?
	V8	Is arrival variation higher than process variation?
	VG16	Is the line balanced?
	VG17	Are there any station(s) that are bottleneck?
	VG18	Is the bottleneck station fed to avoid starvation?
Operations Type	VG312	Is it a PUSH or PULL system? Push (0); Pull (1)
	VG4	Is there a bottleneck in the line?
	VG5	Is the bottleneck station fed to avoid starvation?
	VG6	Is the bottleneck station utilization high or low?
	VG7	What's the CV of the process at the bottleneck station? Low (0) or Other (O - M & H (1))
	VG8	What's the CV of the arrival at the bottleneck station? Low (0) or Other (O - M & H (1))
Priority Branching	VG9	Which of the 4 CRs contribute more to variation? E (0); P (1); S (2); M (3) – follows the priority E, P, S, M
	VG10	Is there a regular maintenance plan which avoids breakdown?
	VG11	Is MTTF high (1) or low (0)
	E. Set Up	What's the batch size? Go to batch size algorithm in Flow
	E. Quality	Decompose Quality of E into Age, Manufacturer, History, Breakdown Frequency and Cost Benefit Analysis (CBA)
People/Schedule	VG19	Is the retention rate high (1) or low (0)?
	VG20	Do the employees have the skills for the job?
	VG21	Is there a robust training plan?
	VG22	Is the schedule for the operations aligned with the schedule of machines, people and materials?
Arrival part 1 and 2	VA1	Is the material arrival on time?
	VA2	Is it early (E) or late (L)?
	VA3	Is the quantity correct?
	VA4	Is the quantity more (M) or less (Le)?
	VA5	Is the quality acceptable?
	VA6	Is the material the right one?
	VA7	Are the specifications correct?
	VA7-1	Is it because of dimensional issues?
	VA7-2	Is it because of color?
	VA7-3	Is it because of density?
	VA7-4	Is it because of stress level deviation?
	VA7-5	All of the above?
	VA7-6	Other – Not listed
Process	VPr1	Is the process automated?
	VPr2	Is it fully (F) or semi (S) automated?
	VPr3	Is the automation more than 50%?
	VPr4	Are the employees skilled & trained for the process?

Table 7. Continued.

Sub Module	Notation used in the Flow chart	Decision Rule / Condition
Placement	VP1	Is the variation same at all stations?
	VP2	Is the first station with most variation?
	VP3	Are there stations after this?
	VP4	Are the remaining stations with same variation?
	VP5	Which remaining station has the highest variation? 0 – None, 1 – Selection
	VP6	Are the stations remaining with same variation?
Updated TF	TF_V	CV of each station and the CV of arrival at the first station Utilization of stations TF with variation

The next step in the algorithm (Figure A.3 corresponding to the submodule 'Operations Type') seeks to identify the type of manufacturing operations; whether it is a push system or a pull system. In a pull system, variation is controlled by the pull mechanism, whereas in a push system it is uncontrollable if the materials are fed into the system (assuming unrestricted physical storage capacity). In reality, there will be limitations on the amount of inventory to be kept between the stations and the total inventory in the system, which will act as a mechanism to block further feed of inventory into the manufacturing system. If this blocking is not introduced in the system, then the impact of variation will become uncontrollable. If it is a push system, the variation at the very first station propagates to the subsequent stations, whereas in a pull system the propagation is in the opposite direction.

Since the variation propagates from one station to the next, the focus should be on the station that starts the process depending on the type of system (push or pull) to be used in the manufacturing operations rather than the bottleneck station. In a pull system, it is better to have the bottleneck station control the pull rather than the last station; materials for stations up to the bottleneck will be pulled and then the bottleneck station will push the material to the next stations down the line. Variation early in the system (first station in the case of a push system and last station in the case of a pull system) is undesirable compared to variation later in the system because of the propagation of variation. If the first station has a high variation of arrival and a high variation of process, then the stations after this will reflect these because of the propagation of variation (Equation 2.17). Controlling the variations at the start station in the line is key to keeping the overall variations and hence the TF low.

There are systems which are extremely time sensitive with respect to variation; as a result, the traditional value of LV systems [3] may not be applicable. Some systems will behave quite differently, even under the accepted range of values for a low variation system (0<CV<0.75 [3]). Hence for such systems, there is a need to consider very low value of CV as acceptable. If the expected coefficient of variation of both the process and arrival are close to zero (as an example a CV of 0.05), then the system may not cause many problems; otherwise the algorithm proceeds to the "four critical resources" [6] (4CRs - Equipment (E), Material (M), People (P), Schedule (S)) and continues its path of computations. Push systems provide opportunity for improvement on a large scale. The coefficient of variation and the availability values will be updated every time the system is improved, thus changing the TF.

The effect of variations on critical resources (CRs) is captured in the algorithm shown in Figure A.4 which corresponds to the submodule ‘Priority Branching’. The order of consideration of the CRs depends on which CR is more prominent than others (which contribute more to variation); the order E, P, S, and M is used. The algorithm looks at repair/maintenance, ramping up effects, setup variations and quality. In repair/maintenance, the most useful information is whether or not the repair happens as a result of the run to failure policy or because of planned maintenance. This policy will have a huge impact on the opportunity for improvement. The repair variability affects the process variation as shown in Equation 2.9 where the variables are c_0, c_r, m_r, t_0 and availability of resources. If the values of the variables are different for each station, then the c_e of each station will be different. Applying the value of the variables for each station in Equation 2.9 will give the c_e of the respective station. Planned maintenances are scheduled ahead of time and hence the manufacturing operations will not be abruptly disturbed.

Changing the decision to go for regular planned maintenance rather than repair in the run to failure mode, will improve the operational time available for production. This change will reduce the CT and hence the TF. In a planned maintenance case, equipment breakdown may not happen because the upgrade or changes are made before failure. The algorithm also looks at variation resulting from quality issues (the factors are given; but not used in the model), as well as the effect of ramping up after setup. In the ramping up, the time lost from the initial start of the process till the full production is to be accounted for (if applicable). In the case of a single product, there will not be any set up changes in between; the only set up needed is at the very beginning of the manufacturing processes. The variability factor will be MTBS / (MTBS + MTTS) where MTBS is the mean time before set-up and the MTTS is the mean time to set up. A sample MATLAB code is given in Appendix C.

The algorithm in Figure A.5, corresponding to the submodule 'People/Schedule', takes into consideration the effect of people variation (lack of skill/training or standard operating procedures) in the system and the schedule/information problems. It is necessary that all the relevant information is available for the person(s) performing the operations. The schedule should be aligned with all the resources. Training and retaining improves the skill of the people which leads to less variation, resulting in a lower coefficient of variation which will in turn lower the TF. This algorithm is pointing to the need of training, retraining and aligning the schedule of all resources. An expected value of availability is fed as a design input for computational purposes, which will result in the TF equation being considered.

The algorithms corresponding to the submodule 'Arrival part 1 and 2' to study about the arrival variations are shown in Figure A.6 and Figure A.7. Arrival variations at the first station are to be controlled; the arrival at the subsequent stations is dependent on the previous stations. For the arrival variations, the issues related to the characteristics of the material (such as quantity, quality, delivery time and schedule) are considered. It looks at the causes listed and informs the decision maker to correct the issues. For the computational aspect, the CV of arrival at the first station is fed as a design input which will reflect in the output value of TF; the arrival processes are tightly controlled. The Process variations are addressed in the algorithms shown in Figure A.8. At the design stage, the values of the CV (corresponding to the type of probability distribution associated with the operations) are fed to check whether the TF is within the TA.

Placement variations are addressed in the algorithm of Figure A.9. The propagation of variation Equation 2.17 applies here (in the actual code the effect of propagation is computed before the TF is calculated based on the values passed from the previous codes to make the code easy to follow). The variables are u_j, c_{ej} and c_{a1}. For the propagation of variation effect to be computed, only the arrival variation at the first station in the line is needed; arrival variations of the subsequent stations are dependent on the departure variations of the previous station. The departure variation of a station is dependent on the arrival variation at the station, process variation and the utilization of the station. In the case of a push system, it would be beneficial if the station with higher variation is the last station in the line; this prevents the high variation propagating to other stations. In a pull system, it is better to have the station with the highest variation at the beginning of the line.

The output of this phase is comprised of the coefficient of variation of arrival and process at each and every station, as well as the utilization of the stations. These are used in the computation of the time to finish with variation effects TF_V by the Equation 3.17 (details of which are in the mathematical computation Section 3.2). The c_a at the second station onward is computed considering the propagation of variation effects given in Equation 2.17. The c_e for each station is computed using Equation 2.9 inputting the corresponding values of the variables for that station. For each station the famous V·U·T equation is applied for the cycle time of the queue. The actual process time is added to it to get the time at each station. This is expanded to get the final time to finish.

4.3 Phase 4 Algorithms for Disruption Design

In this subsection, the algorithms for disruption studies are given. The disruptions design algorithm starts with line related issues followed by material, people and schedule/information disruptions as shown in Figure A.10. Disruption to the bottleneck will affect the performance of the line more than other stations. Downtime, setup changes and yield issues are the main concerns in the line. Reducing downtime is vital to increase the available production time. If the downtime is a result of breakdown, significant improvement could be made by changing to a proactive maintenance plan from a run to failure policy. Reducing setup changes will also improve the production time available. Thus downtimes, as a result of breakdown and setup changes, provide the opportunity for improvement. These are based on the methodology developed in Section 3.6. The logical questions to develop the algorithm are given in Table 8. The notations are used in the flowchart decision boxes. **The availability factor will get updated as a result of the possible changes which will influence the TF; improved availability will reduce the TF.** The algorithms will be looking at the impact of various factors on the availability of the system.

Table 8 Notations for the Disruptions Algorithm

Sub Module	Notation used in the Flow chart	Decision Rule / Condition
Equipment	DE1	Can the number of equipment be changed?
	DE2	Is the cost acceptable?
	DE3	Is there a place to keep the new equipment?
	DE4	Is the TC & PC of the equipment known?
	DE5	Is the PC in acceptable limits?
	OM1	Does the equipment break down frequently?
	OM2	How often? (F – frequently; L – not that often)
	OM3	Is there a repair person available in-house?
	OM4	Is there a robust maintenance plan?
	OM5	Are there plans for preventative & predictive maintenance?
	DE15	What's the reliability of the equipment? (U – unknown; K – known)
	DE17	Is the reliability acceptable?
	DE18	Can it be improved?
	DE20	Are there any issues with equipment scheduling?
	DE22	Is the equipment schedule aligned with People, Material & Schedule of operations?
	DES1	Is the system of single product manufacturing?
	DES2	Is the setup different for products?
	DES3	Are the product families identified?
	DES4	Is the setup time for each family known?
	DES5	Is the setup time separated as internal & external set ups?
	DES6	Is the batch size determined?
	DES7	Is there any way to optimize the batch size?
	Updated Availability Factor for Equipment	A_E
Material	DM1	Is the material requirement computed correctly?
	DM2	Is the number of production runs decided?
	DM3	Is the number of batches per production run decided?
	DM4	Is the quantity per batch decided?
	DM5	Is the schedule of delivery prepared?
	DM6	Is the material available?
	DM7	Is the material schedule aligned with Equipment, People and Schedule of operation?
	Updated Availability Factor for Materials	A_M
People	DP1	Are there enough skilled trained people available in the company?
	DP2	Are there people in the company who can be trained?
	DP3	Are the employees available according to the required schedule?
	Updated Availability Factor for People	A_P
Updated Availability Factor	A	$A = A_E \cdot A_M \cdot A_P \cdot A_S$
Updated TF	TF_D	TF with disruptions

The algorithms to study about the effect of disruptions in manufacturing systems are represented by the flowcharts shown in Figure A.11 to Figure A.17. The notations given in Table 8 are used in the flowcharts. In the repair disruptions algorithm of Figure A.11, the actual repair time (MRT) is only a fraction of the MTTR. Ample time may be spent in organizing, scheduling and getting the parts. If the actual repair time is denoted by MRT (Mean Repair Time) and the time to get full yield after repair as MTTY (Meant Time to Yield) and the time spent to organize as MTTO (Mean Time to Organize), then MTTR is the sum of the three. Mean time to Identify (MTTI), Mean Time to Communicate (MTTC), Mean Time to Assess (MTTA), Mean Time to Determine (MTTD), Mean Time to Locate (MTTL), and Mean Time to Schedule (MTTS) are the subcomponents of MTTO. If the MTTO can be reduced, then the MTTR will also reduce resulting in a better availability value. This is an extension of the work done by [100], [101] and [102].

If the number of machines can be changed in the facility under consideration, a cost benefit analysis is to be carried out before deciding to buy new machines. Also, the capacity of the machines is to be studied, especially the practical capacity (PC). Repair mechanisms are to be incorporated in the case of machines going down. All these are considered in the algorithms shown in Figure A.12 and Figure A.13. The machine scheduling is addressed in the algorithm given in Figure A.14. A sample MATLAB code for the algorithms represented in Figure A.11 Figure A.12 to Figure A.14 is given in Appendix C.

The effect of set up changes on disruption is given in the algorithm shown in Figure A.15. Identifying and classifying into similar product families is crucial in the set-up process. The separation of activities related to set up changes as internal or external is also important. Moving all possible activities as external will reduce the time the line or machine should be shut off. The availability of the material and its schedule is addressed in the Materials Disruptions algorithm in Figure A.16. The algorithm in Figure A.17 looks into the effect of a very important resource for any organization, namely its people. Properly trained and skilled people are an asset to any organization, and they are indeed very critical in the operations. The effect on disruption caused by lack of skilled /trained employees is to be considered in designing systems.

Yield issues are to be considered in designing any system. If a station has a defect rate in the production output, then there is a need to produce more to account for the defective output at that station. These defect rates at the stations will affect the final output of the line. For example, if there are four stations in the line and each station has a defect rate of 10%, then the final output of the line will only be 65%. If materials for 100 units are sent to the first station, the output will only be 90; when this is sent to the next station, the output from that will only be 81 and so on. The final output will only be 65 units! This fact is to be kept in mind at the design stage. Changes in the processes will lead to the defect rate getting reduced in practice.

The time to finish with disruption effects is effectively bringing the value of availability ($A = A_E \cdot A_M \cdot A_P \cdot A_S$) into the equation. This is based on the reliability concept. <u>The values of A_E, A_M, A_P, A_S and A are the output of this phase</u>. The TF_D is found by the Equation 3.18 (details of which are in the mathematical computation Section 3.2). The availability of the four critical resources is always between 0 and 1 (availability is not binary). If all the critical resources are needed, then, using the Cut Vector and Path Vector method does not provide any value. A discussion about cut vector and path vector [79] are given in Appendix A. There will only be one case where the system will work. If any resource is unavailable (availability is zero), then the system availability will be zero. If the resources are available, the system availability will not be zero (it will be any value above zero and up to one depending on the availability of the resources).

4.4 Phase 5 Algorithms for Flow Design

The general discussion about the algorithms for flow design is given in Appendix A. The methodology for these algorithms was discussed in Section 3.7. In this section, the design aspects with respect to the type of flow possible, the batching issues and balancing issues are explained. This dissertation focuses on the batching decision only. Balance design may require facility layout changes and/or inventory level changes. If neither are permitted, the line will remain unbalanced.

A determination of the type of flow possible (Figure A.18 the notations for which are given in Table 13) for the product(s) under consideration is to be carried out. When the questions to this algorithm are answered with the information needed, the flow type possible will either be Single Piece (Balanced or Unbalanced) or Batch processing, which can be Push (CONWIP or non CONWIP) or Pull type. If the existing infrastructure supports single piece balanced manufacturing, there is no need for further design changes. If the product and the manufacturing processes lead to a single piece unbalanced system, then it is to be redesigned to achieve balance or make some corrections so that efficiency can be brought to the system; otherwise it will be the same as a push system. In a push system, inventory is dependent on the production quantity remaining to be completed. If a pull system is the result, then Kanban are to be designed. The block diagram for this discussion is given in Figure A.19. The level of inventory to be kept at this process is dependent on the production rate, process time and the move time. Table 14 in Appendix A gives three cases of comparison.

When k denotes the number of Kanban, D is the demand, L is the lead time, safety stock is denoted by S, and container size by C, then k can be decided by Equation 4.1 [80] which could be used in the algorithm for Figure A.20. However, for this dissertation, the variable $X_{2,}$ in the mathematical model, denotes the number of batches which is a representation of the Kanban. The $X_2 \cdot X_3$ will be the total number of Kanbans needed during the allocated time.

$$k = \frac{D \cdot L\ (1 + S)}{C} \qquad 4.1$$

Since the dissertation focuses on batching and balancing issues, the detailed block diagrams for the batching and balancing issues are shown in Figure 4.3 and Figure 4.4, respectively. The flowcharts for these blocks are given from Figure A.30 to Figure A.36 in Appendix A. A sample code for a level batch size determination algorithm of Figure A.30 corresponding to the block diagram in Figure 4.3 but restricted for a single product is given in Appendix C. Some of the user interface for this code is given in Appendix C Figure C.1**.** Balancing the production line will reduce the operational time and will also smooth out the operations.

The schedule and quantity of material is to be established considering the capacity and schedule of the stations established and also on the flow decision already made. The system must ensure that the scheduling of the materials, people and machines are aligned. It is better to have a just-in-time (JIT) system for the

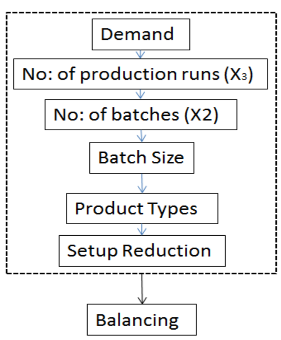


Figure 4.3 Batching block diagram

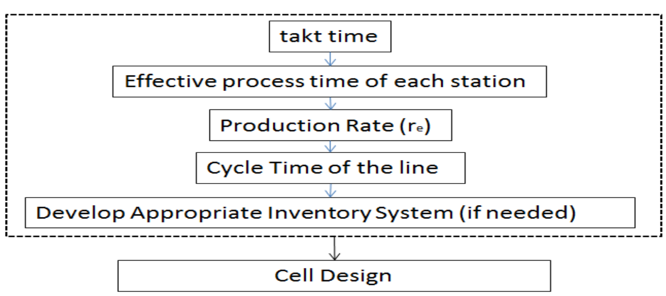


Figure 4.4 Balancing block diagram

inventory, especially between different stages; it eliminates the need for keeping materials in stock. This depends on the product, its maturity, as well as the maturity of the manufacturing system. In some cases, regulatory restrictions restrict the amount of material that can be allowed. In cases where a JIT system is not possible, the material inventory should be limited to what is required for a time period (such as hourly, shift, day, week). Keeping material as inventory always results in waste of resources (such as money and space).

5
VALIDATION AND RESULTS

The methodology is validated using a case study based on a project done at the Oak Ridge National Laboratory (ORNL). The product (plutonium (^{238}Pu)) for the case study hasn't been manufactured in the US for more than three decades and was imported from another country for several years. The foreign country stopped supplying the product and hence the need to restart its production. The product is not currently available elsewhere. The facility where it was previously manufactured was shut down and hence the organization had to look for other locations/facilities. Since the experts, who were instrumental in the manufacturing science behind the product are no longer in service, the production has to start with the basic research. NASA is planning to restart manufacturing of ^{238}Pu in collaboration with DOE using the facilities in Idaho National Lab (INL), Los Alamos National Lab (LANL) and ORNL. Some aspects of the case study are discussed in the papers published in the Journal of Manufacturing Systems 2017 [81] and in an internal report to the facility [82] and also, in the Nuclear and Emerging Technologies for Space (NETS) 2017 conference proceedings [83] respectively. The manufacturing system is to be designed to meet the demand, at the same time taking into consideration the constraints under which the system should function. The main material (the arrival and departure of which is tightly controlled) for this product is owned by the government department (US Department of Energy) and is available.

5.1 Business Case Study for Validation of Model

There are four manufacturing units in this case: Mfgr.1 (Pellet Fabrication), Mfgr.2 (Target Fabrication), Mfgr.3 (Irradiation), and Mfgr.4 (Chemical Processing). The output product from Mfgr.1 could be of different configuration levels (L); this dissertation considers 15 levels. The concentration of the main material in the output product from Mfgr.1 determines the configuration level. Level 15 will have five times more concentration than level 1; compared to level 1, level 5 will have twice the quantity of the main material. The material concentration level will not change once a determination is made for the level selection. The product is still the same irrespective of the material concentration level. The total material required (X_{TOT}) will be different for different levels even when the output quantity required is the same. The composition of material in different configuration levels cannot be published because of national security interests. This level has an effect on the total material required (X_{TOT}); also, the capacity at one of the stations is dependent on this level. For the last unit (Mfgr.4), all the process steps are well developed and cannot be changed. Manufacturing operations are carried out at a facility which is already in existence and the layout cannot be changed. At the end of the allotted time for the operations of this product in the facilities of Mfgr.4, there should not be any materials left over in the process areas (ending WIP should be zero). Mfgr.3 operations are already established and there cannot be any change. The first two units can be designed with machines and the layout planned accordingly. For the purpose of this dissertation, the design of the physical infrastructure is assumed to be ready; only different capacity options will be considered. The manufacturing processes are being developed and modified. There is some information available about the science behind the conversion of the input material to the product; the prototype of the processes are developed. There is no manufacturing run done, so far, except for a few trials with very limited output quantity tested. Simulation was used to study the processes based on the limited data available, and the results were verified with the subject matter experts associated with the case study project. Once all these manufacturing units are complete, an estimate will be given as to how much material is required from the upstream supplier (manufacturer to manufacturer or in the case of the first manufacturer source to Mfgr.1) during a particular time period.

Therefore, the following method is proposed.

A. Identify constraints from a system (top) level.
    I. Identify which of the manufacturing facilities could be changed by adding machines (if needed and if possible).
    II. Identify any facility where no change can be made, even on schedule.
    III. Identify a facility where machines cannot be added but scheduling is possible.
B. Start from the facility where the constraints are the strictest and where machines cannot be added but entire scheduling is open. Design a suitable manufacturing system to meet the customer requirement going down to the constraints at the next level(s).

The four critical resources are connected by some common variables and the task is to identify and estimate them. The different options in the results are then compared.

C. Develop an algorithm to predict the combinations which will produce the required quantity within the constraints defined.

D. Compare the results from the algorithm with the simulated results.

E. Once the last stage of manufacturer is designed, return to the manufactures up-stream and repeat the calculations in the design.

The specific methodology of TF is applied to the chemical processing section which is the last manufacturing unit in the chain. The facilities for this section are shared with other products and hence the time allocated for this product is limited; hence the methodology of TF is applied for this section. The methodology checks whether the design will produce at the expected rate and if so, which of the combinations will produce better results.

5.2 Validation Roadmap

Since the manufacturing processes are being developed and modified, there is not much data available, though some initial data based on the prototype developed is available. There is no manufacturing run done so far except for the prototype developed. The verified simulation results were used as a start point of the development of the validation and results. The prediction from the dissertation model/algorithm is verified by putting the information back to the simulation model.

The algorithms were tested with different combination of values (input data) based on the simulated results; some of the algorithm results were tested manually (using the values of variables and calculating the TF comparing to the actual operations at every station (mapping) and checked as to whether or not the subsequent stations are free to receive the material from the station) to verify that the program is working as intended. Phases 1 and 2 were tested first because the published simulated results reflect only those two phases. The results from the published simulation results and the algorithm mathematical model were statistically analyzed to check the validity of the model. Subject matter experts were consulted at every stage of the development process. Results for phases 3 to 5 were then obtained from the algorithm.

If this model were not developed, simulation models for each and every possible scenario were to be run. The results obtained from the simulation may not be correct, because of its limitations. The reason being the commercial software uses proportions rather than actual computation of percentages or ratios. This model allows input of the values of parameters (such as X_2, X_3, the desired output quantity, the c_{a1}, and c_{ej}), and the results for all possible combinations will be obtained. Comparison was made between the computed values of TF and the TA given by the facility to select the results which satisfy the constraints.

The algorithm results are accurate relative to the accuracy of the mathematical model, which is based on Factory Physics theory. As an example, the published TF of a combination from simulation is 251 days, whereas the TF from the algorithm's mathematical model is 262 days (details given in the results section). The results for the combinations where the utilization of station 1 is between 45% and 55 % in the sub section ‘Comparison of Algorithm and Published Results’ were manually verified by mapping every step and station in the operations. When the utilization is far from 50% at the station where batching occurs, the results will deviate from the actual TF because of the utilization factor in Equation 2.18; this is mentioned in Chapter 3 and in Chapter 6 as a future work.

5.3 Results

The initial main raw material (which is owned by the manufacturing enterprise) is transported from the place of its storage to manufacturer 1 (Mfgr.1). The output product of each manufacturer becomes the important main raw material for the next manufacturer in the chain.

5.3.1 Design for Manufacturer 4 in the Chain

This manufacturing unit (Mfgr.4) does have a time limit with respect to the availability of the facilities for this product and hence the model is applied here. There is an incoming material storage area already in existence for this facility. The materials for the operations of Mfgr.4 will be carried into the first station when necessary. There cannot be any inventory locations in between the process areas. The finished materials from a process will stay in that process area itself unless the subsequent area is free and ready to receive material for processing. This will block the forward movement of processes and hence limit the material inventory between the stations to zero. The final product will be moved to its own storage area. The materials will move from one process area to another automatically once they are released. The facilities are designed for batch processing (and also the material transformation technology requires batch processing) and as such, a single piece flow is not possible. Because of the capacity at each station being different and the significant different processing times at the stations, the line cannot be balanced. The operations in Mfgr.4 use a linear layout. The layout is fixed and the equipment is available and cannot be added or changed. The capacity of the first station in the line (Pr $A_{.1}$) is much less than the other stations; moreover, the technology at the last station (Pr $A_{.4}$) forces the processing time at the station to be dependent on the quantity at its input.

An analysis using phase 1 of the conceptual model with the data (available in [81], [83]) was applied to Equation 3.15: - demand of 1500 units, X_{TOT} is 432, the processing times (t_j) of the four stations respectively are 17 days (includes 4 days to bring the materials and load the station), 14 days, 45 days and 21 days for 300 units at this station (0.07 days for each unit of the product) plus 4 days to remove the product to storage for packing. The analysis indicates that the system can meet the demand in ideal cases (using four batches at the first station (X_{21})). The second station waits for those batches to be processed and available and the system runs two production runs (X_3) and as such, capacity exists. X_{11} is 54 = (428 divided by ($X_2 \cdot X_3$) which is well within the capacity limit of station1. There is no time-consuming start up or shut down operations (compared to the processing time at the stations) for any of the stations in the facility and hence the values of t_{on} and t_{off} are assumed to be zero. There is no additional set up or clean up time for any of the stations and hence t_{sj} and t_{cj} are zero (the time for the final product removal from the station to the storage is already considered). The facility is available for a maximum of 300 days (TA). The resulting TF is 262 days according to the mathematical computation, but the simulated average TF published [81] is only 251 days. Simulations are not an exact mathematical computation and as such the results may not be accurate. This dissertation model results are based on mathematical computation and hence is more accurate. Further analysis depends on using practical conditions as to whether this can be considered as acceptable. Also, this is based on only one of the possible material levels. In an ideal condition, no breakdowns occur. Since this is a single product manufacturing within the time available, no set up changes are needed. Because of the mass balance theory, in practice there is no yield loss. Hence, the actual operational time can be considered as 300 days and as such, the capacity will be checked with respect to this time. So, if the demand can be met within this time frame, the system does have the capacity in ideal conditions.

An analysis using phase 2 of the conceptual model establishes the critical path and determines the bottleneck. There is only one path in the manufacturing processes and hence, it is the critical path. Capacity is tied to the bottleneck, which has high utilization. Utilization is found by computing how much time each process area is processing the materials compared to the TA or the TF; since TF is not yet computed, TA was used. In the initial assessment, station 1 (Pr $A_{.1}$) has more utilization, followed by station 4 and then station 3; in this initial assessment station 1 is processing materials 8 times, whereas the other stations are processing materials only 2 times (four batches are processed by station 1 (X_{21} = 4) before sending it out to station 2) . Since operations at stations 3 and 4 start much later than at station 1, the first station is kept running (by proactive maintenance) to avoid breakdowns. The utilization of the stations' changes, when the number of production runs and the number of batches per run is changed. Since this is a single product system, floating bottlenecks do not occur.

To classify the system, a determination is to be made whether or not it is a stochastic system or a deterministic system. Since the operations are not fully automated, there is a need for employees controlling the operations, at least during the initial stages and then at the finishing stages of each operation at every station. Therefore, the system is not deterministic. As a result, the design starts with consideration of variation effects followed by disruption.

5.3.1.1 Comparison of Algorithm and Published Results

As shown in Table 9 comparison is made to see how the algorithm performs using the developed TF equations when compared with the published results. Equation 3.16 was used for this purpose. All the results, except for one scenario are within 10% if compared between the simulation and mathematical model results. The difference shown in the first seven rows is due to the transfer wait time (TWT) difference between actual and the model. The TWT in the model depends on the utilization of the station; if the utilization is 50%, the equation works perfect, compared to the actual operation. When the utilization increases, the TWT decreases

Table 9 Comparison of Results

Level	Time Increase	Combination X_1, X_2, X_3	Designed Output	Published TF[81], [83]	Algorithm TF	%Change
1	0%	36, 3, 4	1500	295	279	-5.42
1	5%	36, 3, 4	1500	309	287	-7.12
1	10%	36, 3, 4	1500	324	294	-9.26
1	15%	36, 3, 4	1500	339	302	-10.91
1	20%	36, 3, 4	1500	354	310	-12.43
1	25%	36, 3, 4	1500	367	317	-13.62
1	30%	36, 3, 4	1500	381	325	-14.70
1	0%	54, 4, 2	1500	251	262	4.38
1	5%	54, 4, 2	1500	258	270	4.65
1	10%	54, 4, 2	1500	264	277	4.92
1	15%	54, 4, 2	1500	273	284	4.03
1	20%	54, 4, 2	1500	285	292	2.46
1	25%	54, 4, 2	1500	296	299	1.01
1	30%	54, 4, 2	1500	307	306	-0.33
1	0%	49, 3, 3	1500	251	258	2.8
1	5%	49, 3, 3	1500	258	266	3.5
1	10%	49, 3, 3	1500	264	273	4.2
1	15%	49, 3, 3	1500	173	280	3.7
1	20%	49, 3, 3	1500	285	287	1.77
1	25%	49, 3, 3	1500	296	295	0.68
1	30%	49, 3, 3	1500	307	302	-1.63
3	0%	35, 3, 3	1600	249	261	4.82
3	5%	35, 3, 3	1600	253	268	5.93
3	10%	35, 3, 3	1600	256	276	7.81
3	15%	35, 3, 3	1600	261	283	8.43
3	20%	35, 3, 3	1600	272	290	6.62
3	25%	35, 3, 3	1600	284	298	4.93
3	30%	35, 3, 3	1600	296	305	3.04
3	0%	49, 2, 3	1500	223	239	7.17
3	5%	49, 2, 3	1500	226	245	8.49
3	10%	49, 2, 3	1500	234	252	7.69
3	15%	49, 2, 3	1500	245	260	6.12
3	20%	49, 2, 3	1500	255	267	4.71
3	25%	49, 2, 3	1500	266	274	3.01
3	30%	49, 2, 3	1500	276	281	1.81
15	0%	35, 1, 3	1650	202	180	- 10.89
15	5%	35, 1, 3	1650	215	187	-13.02
15	10%	35, 1, 3	1650	224	195	-12.95
15	15%	35, 1, 3	1650	236	202	-14.41
15	20%	35, 1, 3	1650	245	210	-14.29
15	25%	35, 1, 3	1650	254	217	-14.57
15	30%	35, 1, 3	1650	263	225	-14.45
15	0%	21, 2, 3	2000	240	250	4.17
15	5%	21, 2, 3	2000	249	257	3.21
15	10%	21, 2, 3	2000	258	265	2.71
15	15%	21, 2, 3	2000	271	273	0.74
15	20%	21, 2, 3	2000	281	281	0.00
15	25%	21, 2, 3	2000	290	289	-0.34
15	30%	21, 2, 3	2000	299	297	-0.67

whereas it increases when the utilization decreases (based on Factory Physics [3] transfer batch waiting implemented in Equation 2.18).

A statistical analysis for comparing the results from the published simulation and from the algorithm which uses the mathematical computation is shown in Figure 5.1. The null hypothesis that the results are similar is accepted; the p value is very high which indicates that there is no significance to reject the null hypothesis.

5.3.1.2 Results for Phases 3 to 4 - Time to Finish

Design aspects with respect to phases 3, 4 and 5 are presented now. An analysis (Table 10) for a 1500-unit output shows that the system is unbalanced because of both flow issues and variation. This analysis used the Mean Absolute Error Cycle Time Overall (MACTEo), the Coefficient of Variation Overall (CVo) and the Root Mean Square Error Cycle Time Overall (RMSCTEo). Both MACTEo and RMSCTEo are very high, the CVo is more than 0.75; hence the determination that the unbalance is caused by flow issues (high MACTEo) and variation (high CVo).

The TF developed in Section 3.2.2.2 is used to compute the manufacturing time required for Mfgr.4. The process times t1, t2, t3, t4 are of longer duration (in weeks) and hence the process runs continuously (24/7) once it starts. The process areas (stations) are tanks which are connected through pipes. Flow between stations is through automated pipes with valves and pumps. Batch size and the number of production runs are given by the variables X_1, X_2 and X_3. The capacity restriction is for station 1 and hence X1 is the batch size at station1 and this station processes materials X_2 times before station 2 starts processing the whole materials (given by the product of X_1 and X_2) coming out of station 1.

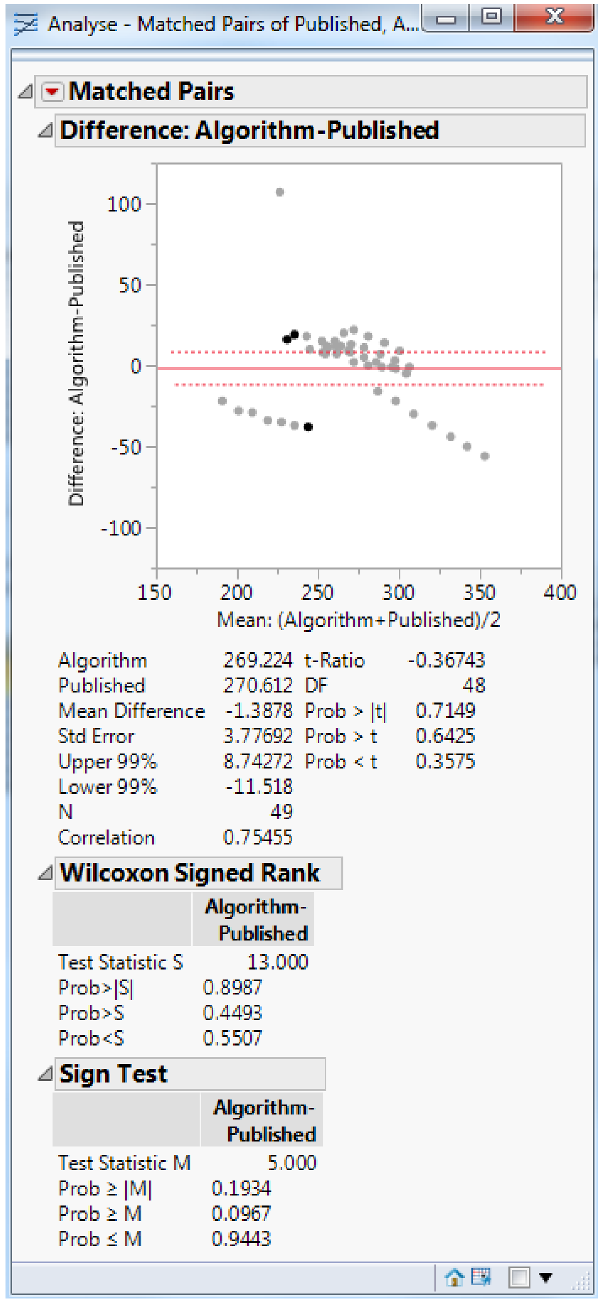


Figure 5.1 Results of paired t test in JMP

Table 10 MACTEo and CVo for Selected Combinations

X_2	X_3	t_1	t_2	t_3	t_4	Mean	SD	MACTEo	CVo	RMSCTEo
1	1	17	14	45	109	46.25	56.6543	31.375	1.22	53.6803
2	1	34	14	45	109	50.5	50.0421	27.125	0.99	46.6485
3	1	51	14	45	109	54.75	48.7515	25.25	0.89	45.2612
4	1	68	14	45	109	59	53.1715	29.5	0.90	49.9908
5	1	85	14	45	109	63.25	62.0944	33.75	0.98	59.3934
1	2	17	14	45	57	33.25	43.9967	18.375	1.32	43.8871
2	2	34	14	45	57	37.5	35.0743	14.125	0.94	34.9368
3	2	51	14	45	57	41.75	33.2071	12.25	0.80	33.0617
4	2	68	14	45	57	46	39.4108	16.5	0.86	39.2884
5	2	85	14	45	57	50.25	50.8105	20.75	1.01	50.7157
1	3	17	14	45	39	28.75	43.7574	17.5	1.52	43.7073
2	3	34	14	45	39	33	34.7737	13.25	1.05	34.7106
3	3	51	14	45	39	37.25	32.8893	11.375	0.88	32.8227
4	3	68	14	45	39	41.5	39.1434	15.625	0.94	39.0874
5	3	85	14	45	39	45.75	50.6034	19.875	1.11	50.5601

Some of the results from the case study are published in a conference [83]. The materials are configured to be of different levels (the concentration of the nuclear material in the assembly is called level in this dissertation). These results are based entirely on the simulation study as reported in the conference paper and the output was 1500, 1650 and 2000 units respectively for option1, option5 and option6 in [83]. The materials in option1 are of level 1; option5 of level 3 and option6 are of level 15. The case study was done to see the effect of increase in the processing time on the output and the time to finish, as well as cycle time.

5.3.1.3 Further Results

The analysis of the information about the availability of the stations is focused on three components, all of which are needed for the station to be used for manufacturing activities. (1) The manipulator has a m_f of 6 months (4320 hours) and a m_r of 4 hours with a SD of 1.15, (2) the pumps which have a m_f of approximately 1 year with a m_r of 2 hours (replacement pumps are available) and (3) valves with a m_f of approximately 6 months with a m_r of 2 hours (replacement valves are available). The manipulator is used more than the other two and hence the computation of the c_e (Equation 2.9) of the stations, the manipulator information is used. Also, the components are used only at the beginning and end of the processes at the stations along with the fact that proactive maintenance exists, which ensures that the components are reasonably reliable. Assuming a c_0 of 0.25, the c_e is 0.250355 on average, which is not significantly different from the c_0; as a result a determination can be made that the stations will behave close to its natural variability because of the station robustness. For the availability of the equipment in disruptions, all three components are used. All the stations are in sequence and hence the series reliability concept is used for the availability factor. The system is unbalanced because of both the process time imbalance and the physical capacity of the tanks being different. Neither the processes nor the stations can be changed and hence a balanced line is not possible. The only possibility in flow design was to look at the batch size determination.

The goal is to produce 1500 units/year. There were 1500 different combinations tested (15 levels * 10 runs * 10 batches per run) and the algorithm selected 278 of them for the ideal case (no variation or disruptions) for Mfgr.4. The time to finish (**TF_{ideal}**) ranges from 150 days to 298 days for the 278 selected combinations whose TF_{ideal} is less than TA. If only level 1 is considered, the range is from 258 to 286 days and there are only 11 possible combinations; for level 15, there are 22 different combinations possible. All the selected values are plotted against its corresponding level in Figure 5.2. When the CV was set to 0.25, each for the arrival and the processes for all stations with availability set to one (applying Equation 3.19 which effectively is the same as Equation 3.17 because of the value of A being 1), only 238 rows were selected (TF <TA). Whereas when the CV was set to 0.5 for the arrival and the process for all stations with availability were set to one, only 168 possible outcomes were selected (Figure 5.3). With the assumption that there is no variation in the system, either in the arrival or in the process in any of the stations (Equation 3.18 used - no variation but disruption exists), an availability of 0.99 on all the critical factors was set to see how the system will perform; 253 rows were selected (TF<TA). When the availability was set to .95 for all the critical resources (with the variation set to zero), the algorithm selected only 57 rows whose TF <TA (Figure 5.4), applying Equation 3.18. When a coefficient of variation of 0.25 was set for the arrival and for all the processes with an expected availability of 0.95 on all four critical resources, (which translates to an effective availability of 0.815 when all of the resources are needed), applied in Equation 3.19, 57 rows were selected to be included where the TF will be less than TA. In both cases, level 1 was not selected (because the TF is more than the TA).

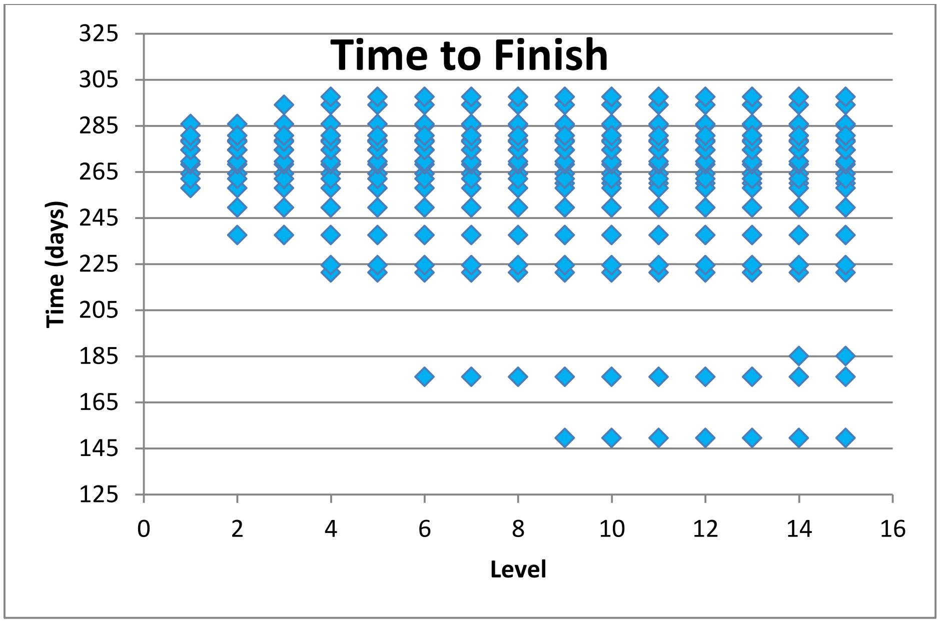


Figure 5.2 Graph of Time versus Level

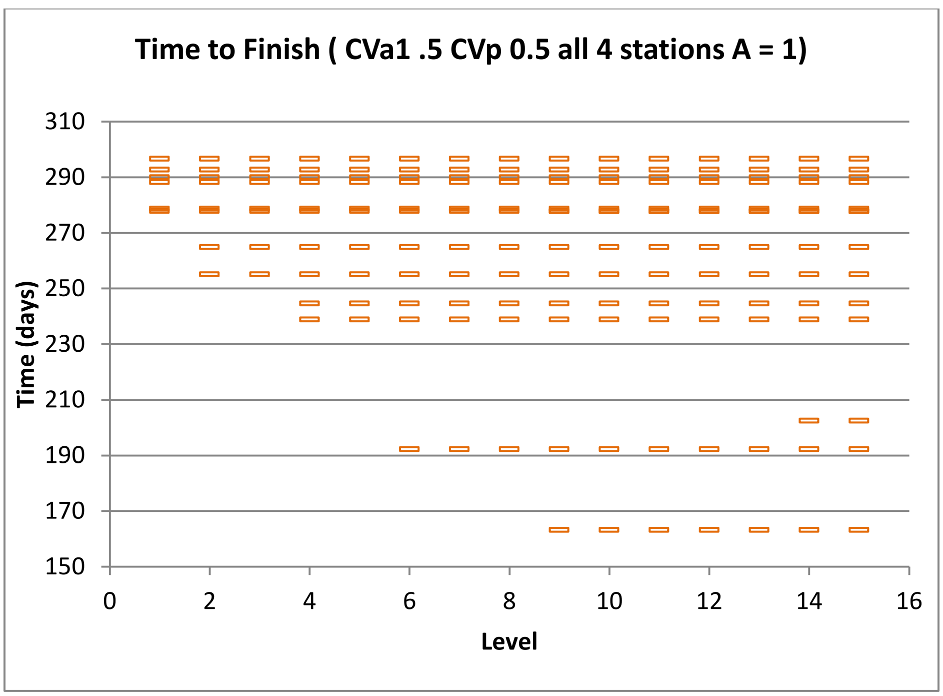


Figure 5.3 TF with CVa and CVp of 0.5 each

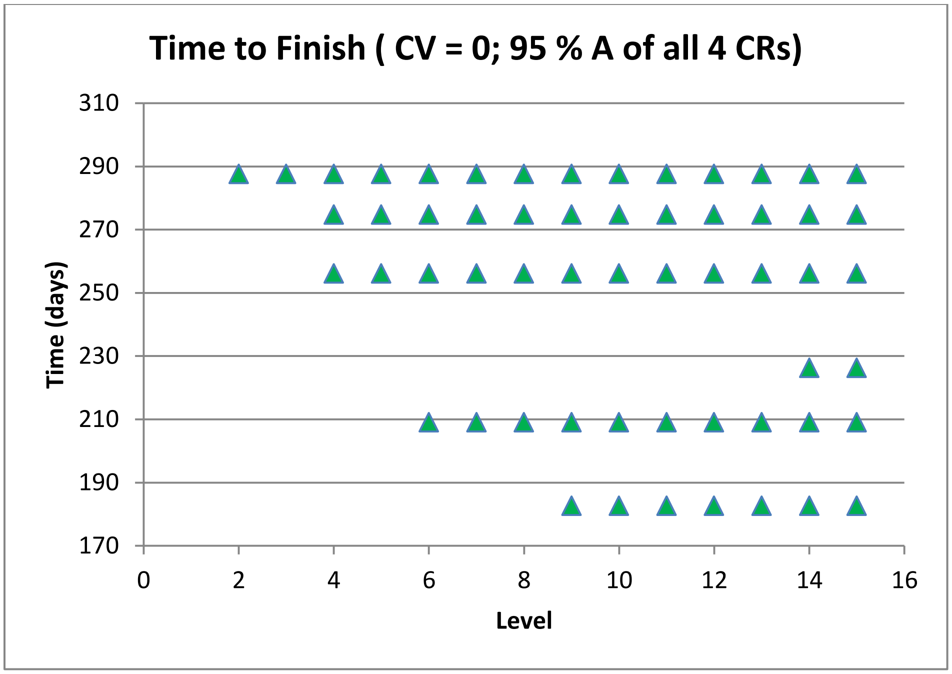


Figure 5.4 TF with no variation and 95% A

As shown in the figures, the level of the material significantly effects time to finish. Also important in each level, is the number of production runs and the number of batches per run; as the number of production runs increases, the time to finish increases for the same number of batches per run. An illustration of the output of the algorithm is shown in Figure 5.5; u_1 – u_4 denotes the utilization of the stations which are computed as the ratio of the time a particular station is used to the time available; c_{a2}, c_{a3} and c_{a4} are computed using the propagation of variation Equation 2.17. This illustration is assuming that the system does not have any variation and a perfect availability of all resources; hence the TF_i, TF_{ideal}, TF_V, TF_D and TF_{VDF} are of the same values. Some selected results for levels 1, 3 and 15 are shown in Table 11.

L	X_2	X_3	TF_i	TF_{ideal}	1 or 0	X_1	X_{TOT}	u1	u2	u3	u4	ca1	ce1	ca2	ce2	ca3	ce3	ca4	ce4	TF_v	Ae	Ap	Am	As	A	TFD	TF_{VDF}
1	2	4	257	264	1	54	432	0.4533	0.1867	0.6000	0.4033	0	0	0	0	0	0	0	0	264	1	1	1	1	1	264	264
1	3	3	260	258	1	48	432	0.5100	0.1400	0.4500	0.3900	0	0	0	0	0	0	0	0	258	1	1	1	1	1	258	258
1	3	4	315	279	1	36	432	0.6800	0.1867	0.6000	0.4033	0	0	0	0	0	0	0	0	279	1	1	1	1	1	279	279
1	4	2	252	262	1	54	432	0.4533	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	262	1	1	1	1	1	262	262
2	4	3	309	268	1	29	348	0.6800	0.1400	0.4500	0.3900	0	0	0	0	0	0	0	0	268	1	1	1	1	1	268	268
3	2	3	214	238	1	48	288	0.3400	0.1400	0.4500	0.3900	0	0	0	0	0	0	0	0	238	1	1	1	1	1	238	238
15	1	1	185	185	1	96	96	0.0567	0.0467	0.1500	0.3633	0	0	0	0	0	0	0	0	185	1	1	1	1	1	185	185
15	1	2	150	150	1	48	96	0.1133	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	150	1	1	1	1	1	150	150
15	1	3	176	176	1	32	96	0.1700	0.1400	0.4500	0.3900	0	0	0	0	0	0	0	0	176	1	1	1	1	1	176	176
15	1	4	221	221	1	24	96	0.2267	0.1867	0.6000	0.4033	0	0	0	0	0	0	0	0	221	1	1	1	1	1	221	221
15	4	2	252	262	1	12	96	0.4533	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	262	1	1	1	1	1	262	262
15	6	2	320	275	1	8	96	0.6800	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	275	1	1	1	1	1	275	275
15	7	2	354	278	1	7	98	0.7933	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	278	1	1	1	1	1	278	278
15	8	2	388	281	1	6	96	0.9067	0.0933	0.3000	0.3767	0	0	0	0	0	0	0	0	281	1	1	1	1	1	281	281

Figure 5.5 Illustration of sample algorithm output

Table 11 Some Selected results

Level	Combination (X_{11}, X_2, X_3)	Variation	Availability	Designed Output	TF (days)
1	54, 4, 2	0 0 0 0 0	1 1 1 1	1500	262
1	54, 4, 2	.25 .25 .25 .25 .25	1 1 1 1	1500	267
1	54, 4, 2	.33 .33 .33 .33 .33	1 1 1 1	1500	270
1	54, 4, 2	.5 .5 .5 .5 .5	1 1 1 1	1500	279
1	54, 4, 2	0 0 0 0 0	.99 .99 .99 .99	1500	273
1	54, 4, 2	0 0 0 0 0	.95 .95 .95 .95	1500	N/A (**321**)
1	54, 4,2	0 0 0 0 0	.95 1 1 1	1500	276
1	54, 4, 2	.25 .25 .25 .25 .25	.99 .99 .99 .99	1500	277
1	54, 4, 2	.25 .25 .25 .25 .25	.95 .95 .95 .95	1500	N/A (**326**)
1	54, 4, 2	.25 .25 .25 .25 .25	.95 1 1 1	1500	280
1	54, 4, 2	.25 .25 .25 .25 .25	.95 .99 .99 .99	1500	289
3	48, 2, 3	0 0 0 0 0	1 1 1 1	1500	238
3	48, 2, 3	.25 .25 .25 .25 .25	1 1 1 1	1500	242
3	48, 2, 3	.33 .33 .33 .33 .33	1 1 1 1	1500	246
3	48, 2, 3	.5 .5 .5 .5 .5	1 1 1 1	1500	256
3	48, 2, 3	0 0 0 0 0	.99 .99 .99 .99	1500	247
3	48, 2, 3	0 0 0 0 0	.95 .95 .95 .95	1500	289
3	48, 2, 3	0 0 0 0 0	.95 1 1 1	1500	250
3	48, 2, 3	.25 .25 .25 .25 .25	.99 .99 .99 .99	1500	252
3	48, 2, 3	.25 .25 .25 .25 .25	95 .95 .95 .95	1500	293
3	48, 2, 3	.25 .25 .25 .25 .25	.95 1 1 1	1500	254
3	48, 2, 3	.25 .25 .25 .25 .25	.95 .99 .99 .99	1500	261
15	16, 2,3	0 0 0 0 0	1 1 1 1	1500	238
15	16, 2,3	.25 .25 .25 .25 .25	1 1 1 1	1500	242
15	16, 2,3	.33 .33 .33 .33 .33	1 1 1 1	1500	246

Table 11. Continued.

Level	Combination (X_{11}, X_2, X_3)	Variation	Availability	Designed Output	TF (days)
15	16, 2,3	.5 .5 .5 .5 .5	1 1 1 1	1500	256
15	16, 2,3	0 0 0 0 0	.99 .99 .99 .99	1500	247
15	16, 2,3	0 0 0 0 0	.95 .95 .95 .95	1500	288
15	16, 2, 3	0 0 0 0 0	.95 1 1 1	1500	250
15	16, 2, 3	.25 .25 .25 .25 .25	.99 .99 .99 .99	1500	252
15	16, 2, 3	.25 .25 .25 .25 .25	95 .95 .95 .95	1500	293
15	16, 2, 3	.25 .25 .25 .25 .25	.95 1 1 1	1500	254
15	16, 2, 3	.25 .25 .25 .25 .25	.95 .99 .99 .99	1500	261
15	32, 1,3	0 0 0 0 0	1 1 1 1	1500	176
15	32, 1,3	.25 .25 .25 .25 .25	1 1 1 1	1500	181
15	32, 1,3	.33 .33 .33 .33 .33	1 1 1 1	1500	184
15	32, 1,3	.5 .5 .5 .5 .5	1 1 1 1	1500	193
15	32, 1,3	0 0 0 0 0	.99 .99 .99 .99	1500	182
15	32, 1,3	0 0 0 0 0	.95 .95 .95 .95	1500	210
15	32, 1, 3	0 0 0 0 0	.95 1 1 1	1500	184
15	32, 1, 3	.25 .25 .25 .25 .25	95 .95 .95 .95	1500	214
15	32, 1, 3	.25 .25 .25 .25 .25	.95 1 1 1	1500	188
15	32, 1, 3	.25 .25 .25 .25 .25	.95 .99 .99 .99	1500	193

The model computed the values of X_1, X_2, and X_3, as well as the values of TF using the applicable equation for each instance. The values of the processing time of the stations, the CV and availability (A_E, A_M, A_P, A_S) were fed as inputs (this is a design problem and as such these parameter values are used to test the design). As shown in the results above, this manufacturing system is very sensitive to both variations and disruptions. Also, the material level is another factor which will play a part in the sensitivity of the time to finish.

5.3.2 All Manufacturers in the Chain

The manufacturing system for the whole chain is designed with the assumption that the organization will be able to keep the variations (if any) at a minimum level (CV of 0.25 for arrival as well as processes) and the critical resources of people, material and schedule have an availability of 0.99. The facility (equipment) availability is set to 0.95 (which makes the combined availability of all four CRs to 0.9218). If the product quantity required from Mfgr.3 is more than what the nearest location can supply, a penalty equivalent to half a year of time is introduced to account for the two-way transportation (the process is very complex). Also assumed is that Mfgr.1 can produce enough quantity of its output product required for 7 products of Mfgr.2 output product in 2 days (Mfgr.2 starts its operations once enough material for 7 of its output product is available). The maximum capacity of Mfgr.1 is restricted per shift because of an equipment capacity limit. Also assumed is that Mfgr.1 and Mfgr.2 will have 250 working days per year (assuming a 5-day work week and 50 weeks per year) to account for employees taking 2 weeks' vacation). Mfgr.2 can process the materials supplied by Mfgr.1 in the sequence. The total time of manufacturing through the whole chain is computed based on the TF of each of the manufacturers in the chain. The TF for Mfgr.1 and Mfgr.2 are estimated based on a base capacity. It can be changed based on adding more capacity. The total time is between 320 days and 1,116 days. This is proof that the level of the material has a significant effect on the time to complete the manufacturing processes through the whole chain. All the combinations possible with level 1 take more than 1,100 days, whereas material with level 15 takes between 320 and 458 days. The results are plotted in Figure 5.6.

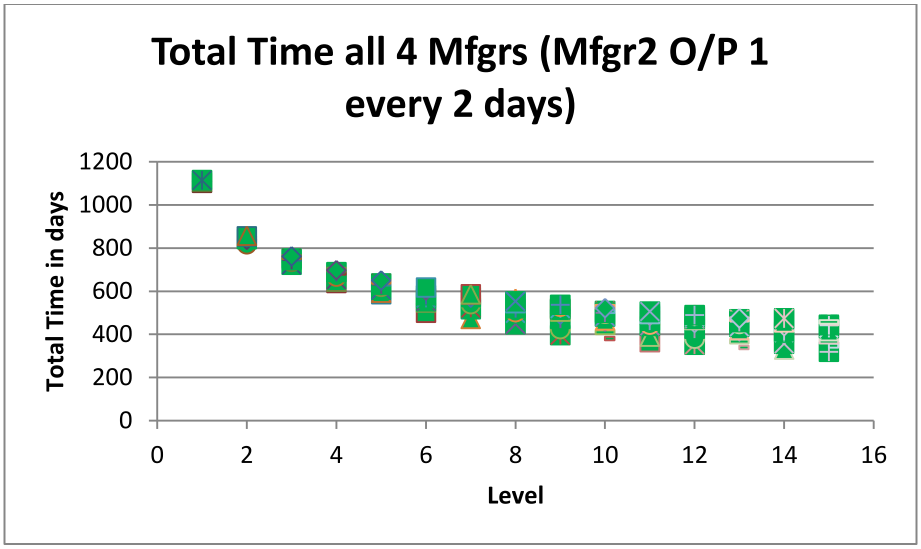


Figure 5.6 Graph of Total Time versus Level case1

If the Mfgr.1 production can be doubled (by adding a shift or line), then the total time to complete the manufacturing processes for all the manufacturers together will be between 300 and 1,025 days. All possible combinations with level 1 will take 1,012 to 1,024 days, whereas material with level 15 takes between 300 and 437 days.

5.4 Recommendations

With the information provided so far, it will be better for the organization to go for the higher level materials than with level 1 or level 3. If level 15 cannot be used because of the issue of getting regulatory approval, materials with concentration levels 7 to 9 (level 7 will have half of the material concentration compared to level 15) should be considered. This will make the total manufacturing time in the chain 406 to 548 days instead of more than 1,000 days if level 1 material is used. The results for all 31 combinations with levels 7 to 9 are given in Table 12 with the CV set to 0.25 for the initial arrival process, as well the stations and the availability was 0.95 for the equipment and 0.99 for the other three resources. Assuming a 45-day time buffer (which will make sure that all operations definitely finishes in 255 days) for Mfgr.4, there will be 10 different combinations selected for manufacturing operations. Assuming a 30-day time buffer for Mfgr.4, there will be 12 combinations selected, whereas with a 15 day time buffer, there will be 15 combinations to select from. It is assumed that $Mfgr._1$ and $Mfgr._2$ will be able to finish the assembly operation within the time shown.

Table 12 Recommended Combination of Results

Level	X_2	X_3	TF_i		X_1	X_{TOT}	u1	u2	u3	u4	TF_V	TF_D	TF_{VDF}	Time Mfgr3	Time Mfgr43	Time Mfgr2	Time Mfgr432	Time Mfgr1	Time Mfgr4321
7	1	3	176	1	58	174	0.170	0.140	0.450	0.390	180	188	193	170	363	36	399	36	435
7	1	4	221	1	43	172	0.227	0.187	0.600	0.403	227	234	241	168	409	36	444	36	480
7	2	2	225	1	43	172	0.227	0.093	0.300	0.377	228	243	247	168	415	36	451	36	487
7	2	3	238	1	29	174	0.340	0.140	0.450	0.390	242	256	261	170	431	36	467	36	504
7	2	4	264	1	22	176	0.453	0.187	0.600	0.403	271	284	291	172	463	37	499	37	536
7	3	2	250	1	29	174	0.340	0.093	0.300	0.377	253	270	274	170	444	36	481	36	517
7	3	3	258	1	20	180	0.510	0.140	0.450	0.390	263	279	284	176	460	38	498	38	535
7	4	2	262	1	22	176	0.453	0.093	0.300	0.377	266	284	288	172	460	37	497	37	534
7	4	3	268	1	15	180	0.680	0.140	0.450	0.390	274	290	297	176	473	38	510	38	548
7	5	2	270	1	18	180	0.567	0.093	0.300	0.377	274	292	297	176	473	38	511	38	548
8	1	3	176	1	53	159	0.170	0.140	0.450	0.390	180	188	193	155	348	33	381	33	414
8	1	4	221	1	40	160	0.227	0.187	0.600	0.403	227	234	241	156	397	33	430	33	463
8	2	2	225	1	40	160	0.227	0.093	0.300	0.377	228	243	247	156	403	33	436	33	470
8	2	3	238	1	27	162	0.340	0.140	0.450	0.390	242	256	261	158	419	34	453	34	487
8	2	4	264	1	20	160	0.453	0.187	0.600	0.403	271	284	291	156	447	33	480	33	513
8	3	2	250	1	27	162	0.340	0.093	0.300	0.377	253	270	274	158	432	34	466	34	500
8	3	3	258	1	18	162	0.510	0.140	0.450	0.390	263	279	284	158	442	34	476	34	510
8	4	2	262	1	20	160	0.453	0.093	0.300	0.377	266	284	288	156	444	33	478	33	511
8	4	3	268	1	14	168	0.680	0.140	0.450	0.390	274	290	297	164	461	35	496	35	531
8	5	2	270	1	16	160	0.567	0.093	0.300	0.377	274	292	297	156	453	33	486	33	520
9	1	2	150	1	72	144	0.113	0.093	0.300	0.377	153	162	166	141	307	30	337	30	367
9	1	3	176	1	48	144	0.170	0.140	0.450	0.390	180	188	193	141	334	30	364	30	394
9	1	4	221	1	36	144	0.227	0.187	0.600	0.403	227	234	241	141	382	30	412	30	442
9	2	1	260	1	72	144	0.113	0.047	0.150	0.363	264	282	287	141	428	30	458	30	488

Table 12. Continued.

Level	X_2	X_3	TF_i		X_1	X_{TOT}	u1	u2	u3	u4	TF_V	TF_D	TF_{VDF}	Time Mfgr3	Time Mfgr43	Time Mfgr2	Time Mfgr432	Time Mfgr1	Time Mfgr4321
9	2	2	225	1	36	144	0.227	0.093	0.300	0.377	228	243	247	141	388	30	418	30	448
9	2	3	238	1	24	144	0.340	0.140	0.450	0.390	242	256	261	141	402	30	432	30	462
9	2	4	264	1	18	144	0.453	0.187	0.600	0.403	271	284	291	141	432	30	462	30	492
9	3	2	250	1	24	144	0.340	0.093	0.300	0.377	253	270	274	141	415	30	446	30	476
9	3	3	258	1	16	144	0.510	0.140	0.450	0.390	263	279	284	141	425	30	455	30	485
9	4	2	262	1	18	144	0.453	0.093	0.300	0.377	266	284	288	141	429	30	459	30	489
9	4	3	268	1	12	144	0.680	0.140	0.450	0.390	274	290	297	141	438	30	468	30	498

6
CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The processes of designing a manufacturing system properly were studied and an algorithm was developed which will aid in the design. This approach considered the effect of variations and disruptions on the timely completion of any process at the design stage itself and will help the decision makers plan for such cases. The algorithm was implemented as a model driven, rule-based program in MATLAB which is an application of the model. The model was tested and validated comparing the simulated results with the model results. An interactive graphical user interface (GUI) was developed to feed the values of variables, which are to be tested with the model, a sample of which is provided in Figure C.2. The MATLAB code for this is given in Appendix C.

6.2 Future Work

The WT_{factor} is empirically estimated in this dissertation. This is an area which needs further research to come up with a better mathematical formulation. The application of the concepts of variation and disruption affecting the performance of any system is to be expanded to improve upon the formulations. The framework and the algorithm discussed could be improved. This dissertation is the base work of a future expansion about these topics. The exact TF for $Mfgr._2$, $Mfgr._3$ and $Mfgr._4$ is to be computed using the Equation 3.19 once the processes are finalized and the processing time and capacity at each individual process are known. The startup, shutdown, set up and the cleanup time could be stochastic in nature; further research is needed to update the mathematical model to reflect this. More study could be done about the concept of floating bottlenecks, but it requires the manufacturing of more than one product by the system to be analyzed. The model could also be studied with significant disruptions occurring at stations other than the present bottleneck to see whether the concept can be used in a single product manufacturing line.

A level batch size was considered as part of this dissertation. It could be improved by adding algorithms to make it variable between a lower limit and upper limit using appropriate and suitable methods. Further study is needed in regards to making the transfer wait time (TWT) more in tandem with the actual wait time. Since the Factory Physics equation uses utilization of the station in the denominator, the transfer wait time (if applicable) departs real life wait time in both directions. The wait time computed by using the Factory Physics equation will be exceeded in the actual case when the utilization is very low and vice versa; the wait time equation works perfectly when the utilization of the station is 50%. Further research is needed when it comes to adjusting the TWT which accommodates for the deviation from reality in both directions. Also, any other factors which need further study are to be covered in future research. The impact of variation and disruptions caused by people are to be studied and a mathematical model needs to be developed with respect to time. The concepts of reverse engineering could be applied to designing operational manufacturing system in the future.

6.3 Generalization of the Model to all Manufacturing

The algorithms can be applied to any single product manufacturing system with some modifications to the mathematical model which will reflect the type of processing used for the particular system. Most of the manufacturing is sequential in nature with predetermined steps and routes. With modification to the TF equations, the exact time to finish could be determined, which will then give some idea about when the production processes will end for the quantity demanded. Care should be taken about the effect of utilization in the results. It will be decided whether or not the WT_{factor} is appropriate for the type of processing and inventory controls. This model could be applied from a single user perspective to scale up production to the required quantity. It could also be used as a production planning tool by the facility managers to effectively schedule the operations.

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APPENDICES

Appendix A

Phase 1 – Numerical Example of TF computation

Applying assumed values for X_3, X_{21}, Y, X_{14} and t_j (for validation, the number of production runs and the number of batches per run are computed by applying Equations 3.7 and 3.8; the demand (Y) is the required throughput of the system), to the Equation 3.15 TF_i is computed here. If there are four stations and the processing time at each station is 10 (same unit of time), $X_{21} = 4$, $X_3 = 3$, $Y = 300$, $X_{14} = 100$, then we get TFi as 156.75 units of time (with an empirical estimation of WT_{factor} as $((X_3)^3)/X_{2j}$. If the TA is 240, then, in ideal conditions, the facility has the capacity to meet the demand and has a buffer of 83 units of time.

Phase 2 – Flowchart and Numerical Example of TF computation

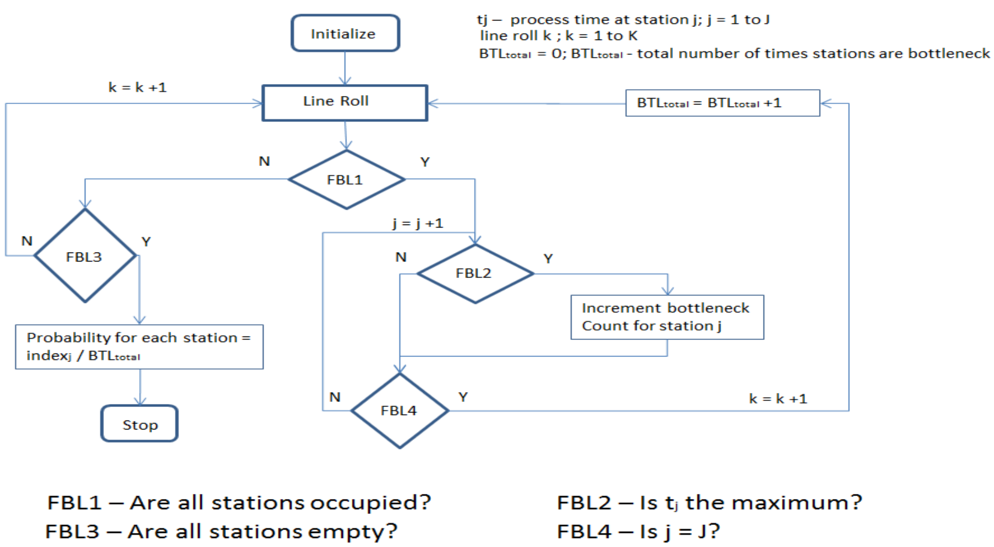


Figure A.1 Algorithm for Floating Bottleneck

Example of TF computation for phase 2: If there is only one path in the process diagram, that path is definitely the critical path. Manufacturing operations for a single product is usually comprised of one single path. If there are four stations and the processing time at each station is 10 (same unit of time), X_{21} = 4 (batching at station1), X_3 = 3, Y = 300, X_{14} =100 (station4 is single unit processing station), TA = 240, the utilization of stations are: u_1 = (4*3*10)/240 = 0.5, u_2 = u_3 =u_4 = 30/240 = 0.125. The first station is the bottleneck. The recomputed time to finish (TF_{ideal}) is 156.75 units of time by applying these values to Equation 3.16. This is exactly equal to the TF_i in phase 1 because u_1 is 50%. This system may be able to withstand variations and disruptions because there are still 83 units of time left (almost 35%) in the allocated/available time. The actual system is to be tested with variable values obtained from the facility.

Phase 3 – Flowcharts and Numerical Example

The flowcharts of the algorithms discussed in Section 4.2 are given here. The notations used in the flowcharts are given in Table 7.

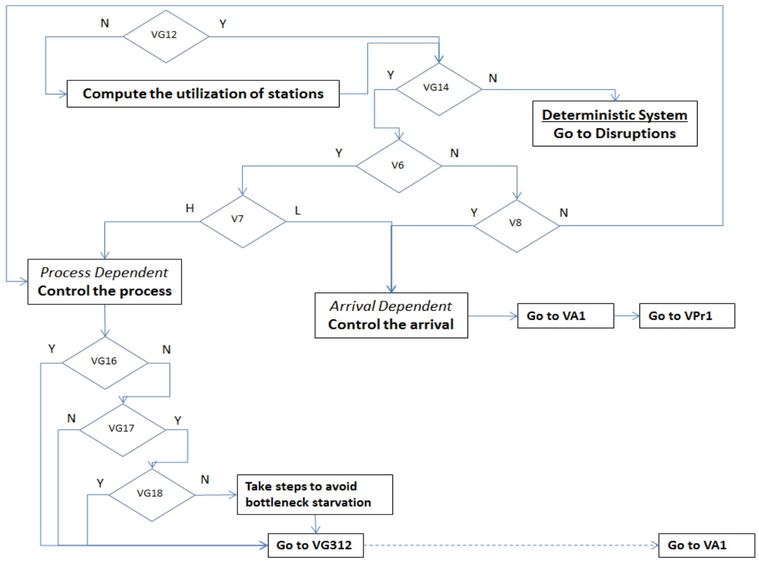


Figure A.2 Design for Variations (V) part 1 – Process Control

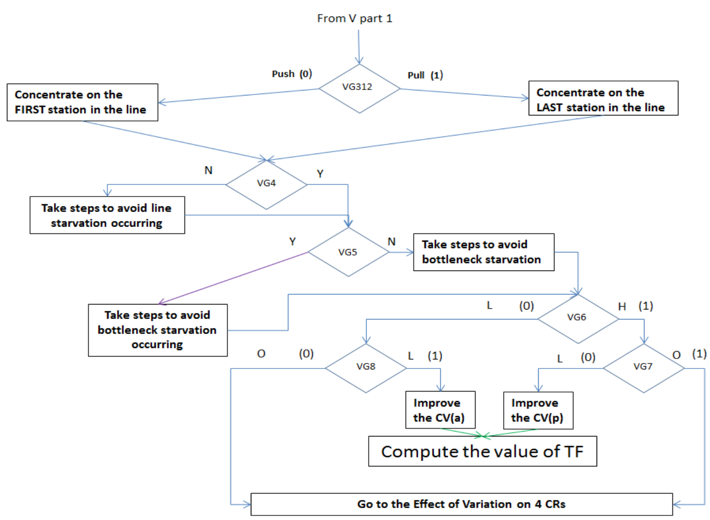


Figure A.3 Design for Variations (V) part 2 – Operations Type

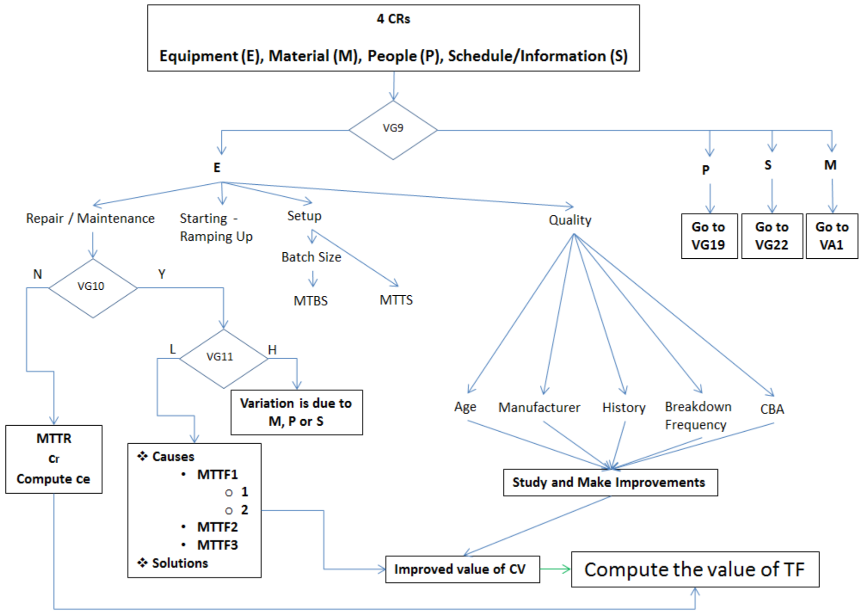


Figure A.4 Design for Variations (V) part 3 – Priority Branching

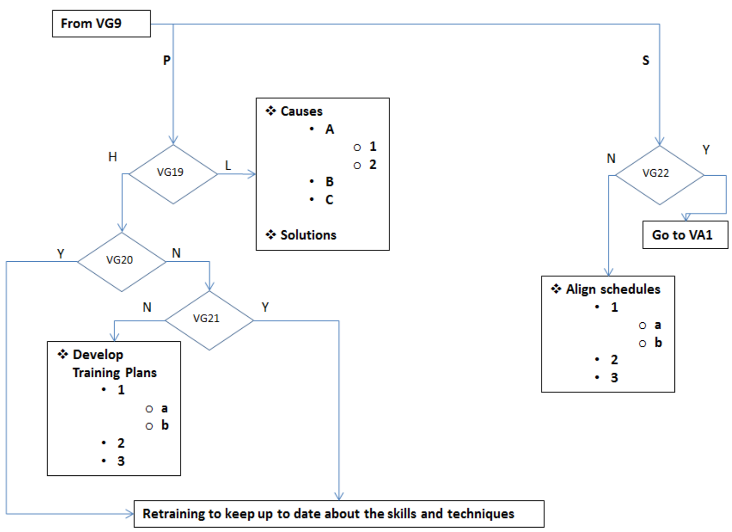


Figure A.5 Design for Variations (V) part 4 – People and Schedule

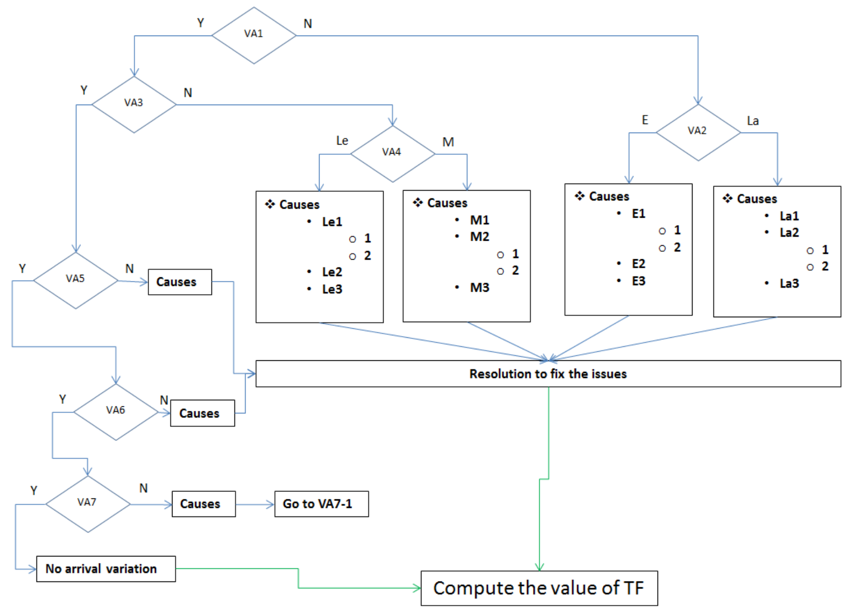


Figure A.6 Design for Variations (V) part 5 – Arrival part1

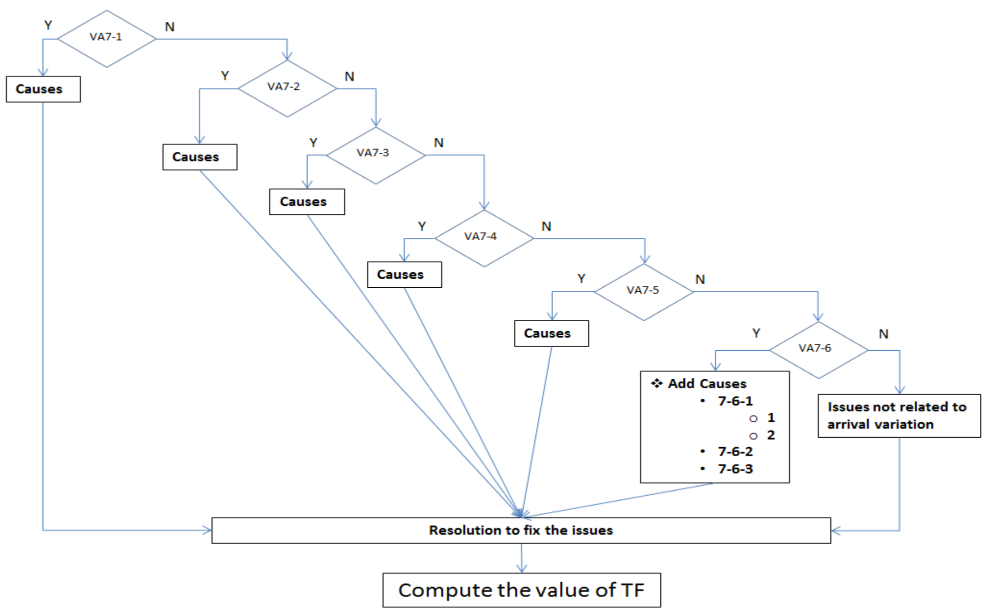


Figure A.7 Design for Variations (V) part 6 – Arrival part2

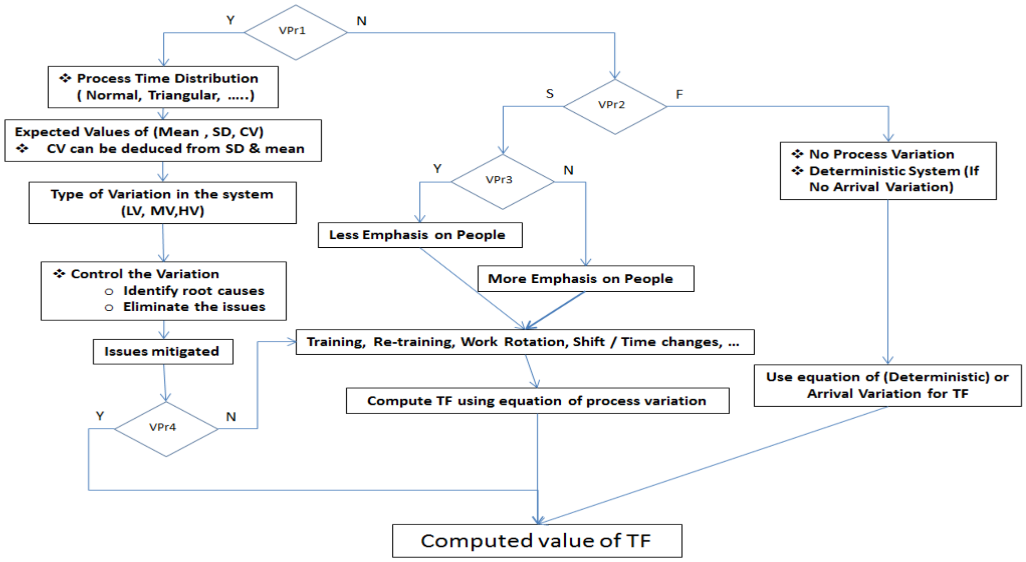


Figure A.8 Design for Variations (V) part 7 – Process

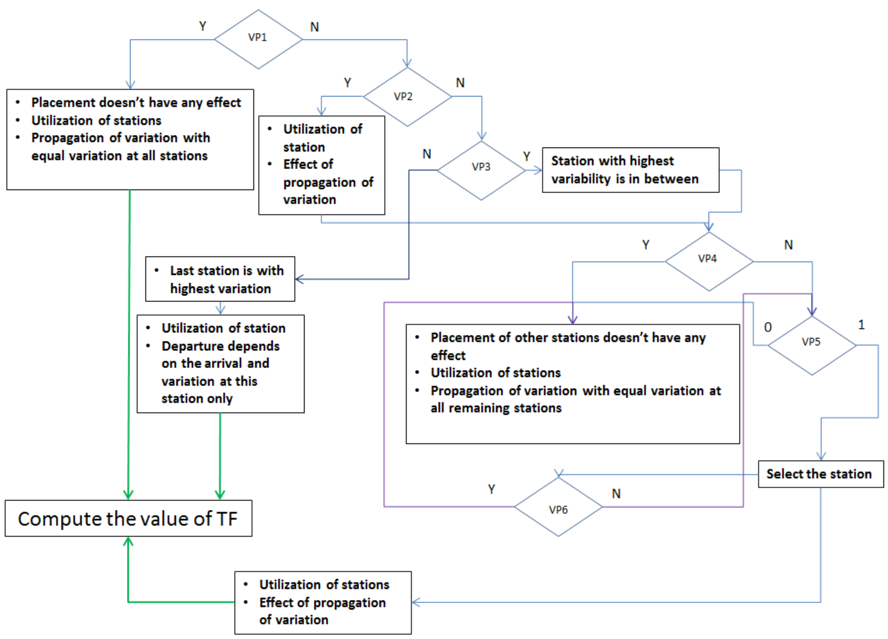


Figure A.9 Design for Variations (V) part 8 – Placement

Example of TF computation for Phase 3: Assume c_{a1} = 0.2, natural coefficient of variation of all stations (c_{oj}) is 0.24. Utilization of stations are computed in phase 2 as u_1 = 0.5, u_2=u_3=u_4 = 0.125. Step1: The CV of stations (c_{ej}) are computed using Equation 2.9 with assumed values of A = 0.95, m_r = 4, c_r = 0.33 for all stations (for validation, the actual values obtained from the facility is used); $c_{e1} = c_{e2} = c_{e3} = c_{e4}$ = 0.28048. The values assumed here are kept the same for computational easiness; in reality the values for each station may be different. The same unit of time is used for all variables associated with time. Step2: The CV of arrival at station 2 is computed using Equation 2.14 as: $c_{a2} = c_{d1} = \sqrt{}\ ((0.5)^2 * (0.28048)^2 + (1-(0.5)^2) * 0.2 = 0.222862$. Similarly, c_{a3} = 0.223876 and c_{a4} = 0.22487. Step3: Applying these values to the Equation 3.20 the TF_V is computed as 157.6193 which is only slightly more than the TF_{ideal}.

Phase 4 – Flowcharts and Numerical Example

The notations used in the flowcharts for this phase are given in Table 8.

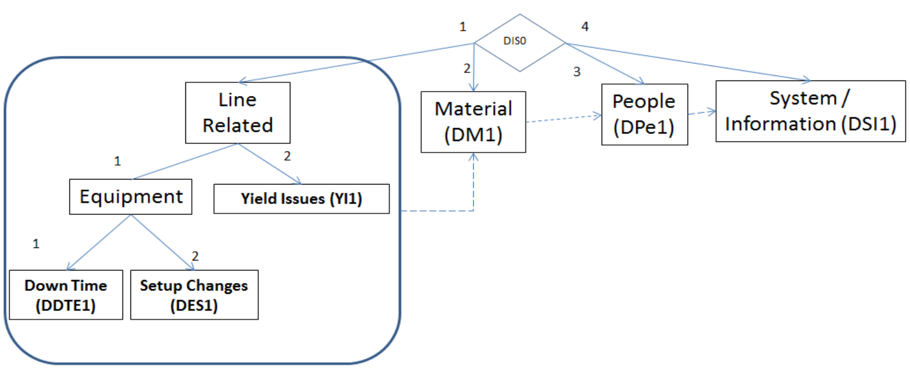


Figure A.10 Disruptions Algorithm Design General - DIS0 represents the priority of the 4CRs

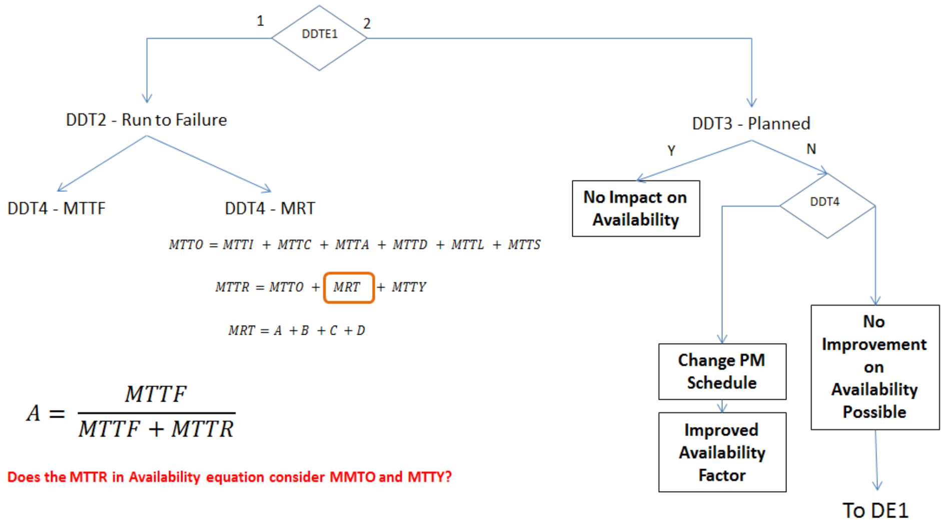


Figure A.11 Failure, Repair and Planned Disruptions

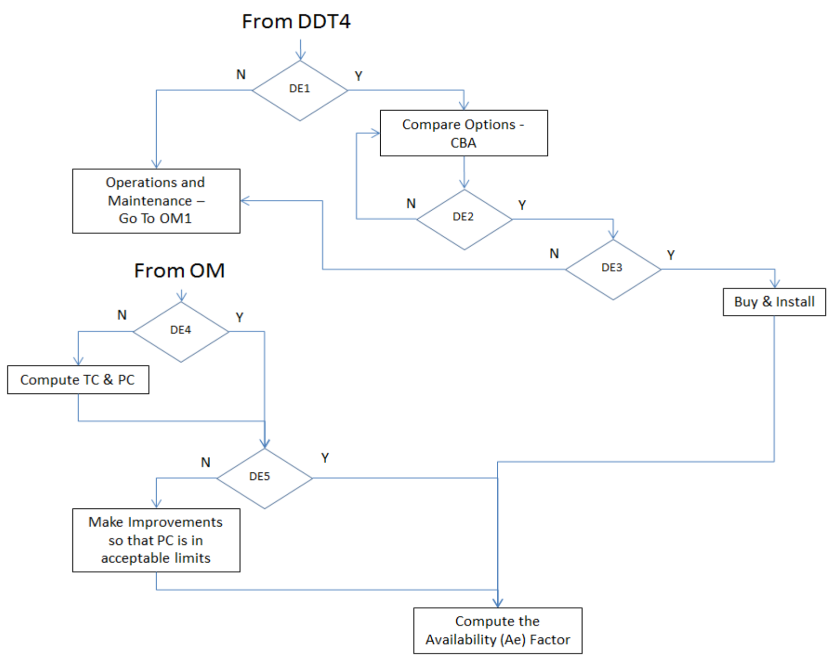


Figure A.12 Equipment / Machine Disruptions Algorithm part1

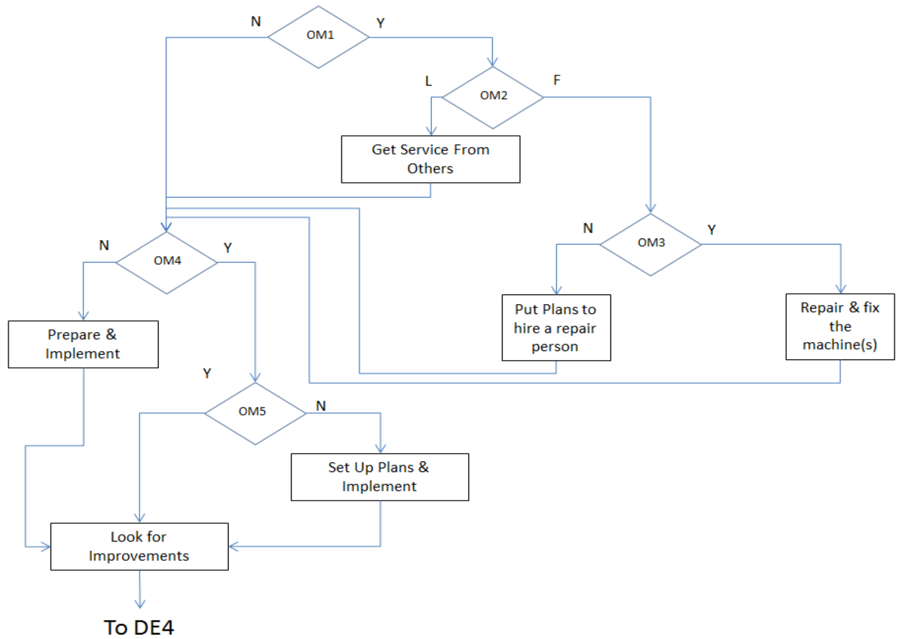


Figure A.13 Machine Disruptions Algorithm – Operations & Maintenance

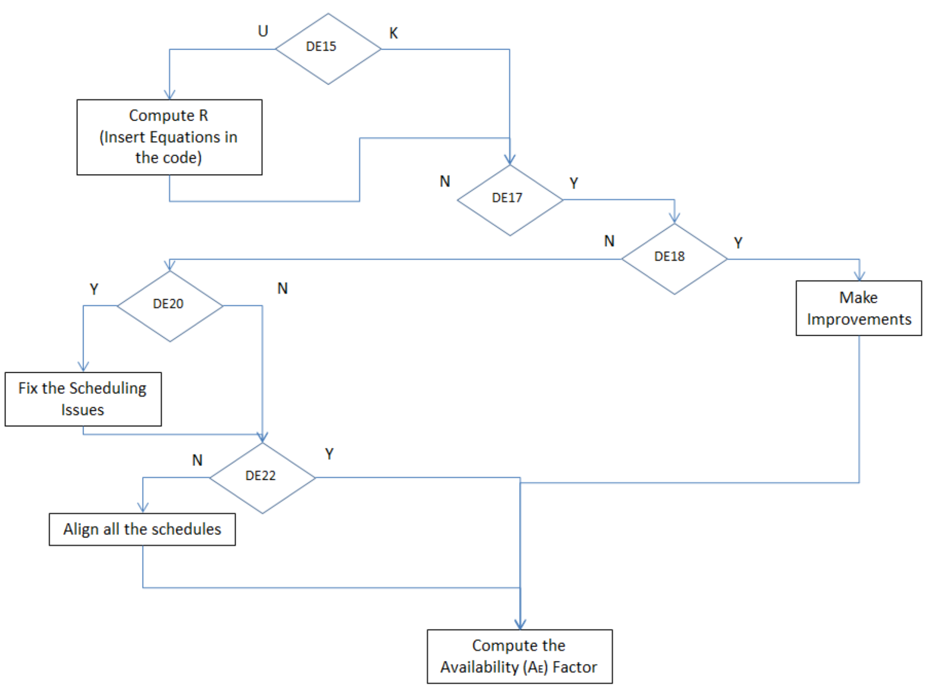


Figure A.14 Machine Disruptions Algorithm – Scheduling

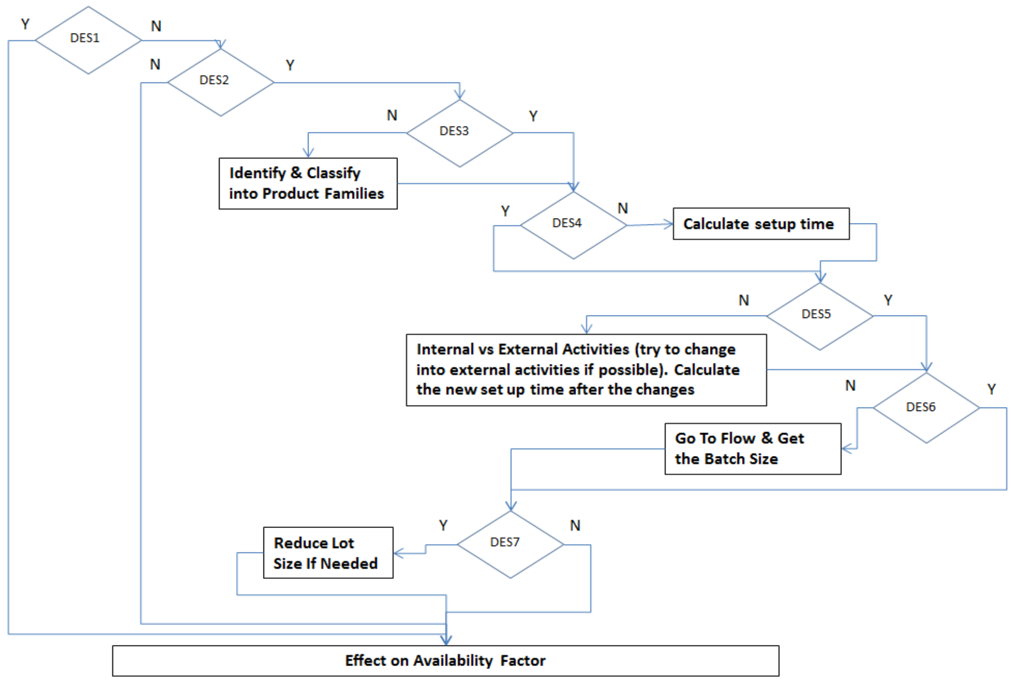


Figure A.15 Set Up Changes Disruption Algorithm

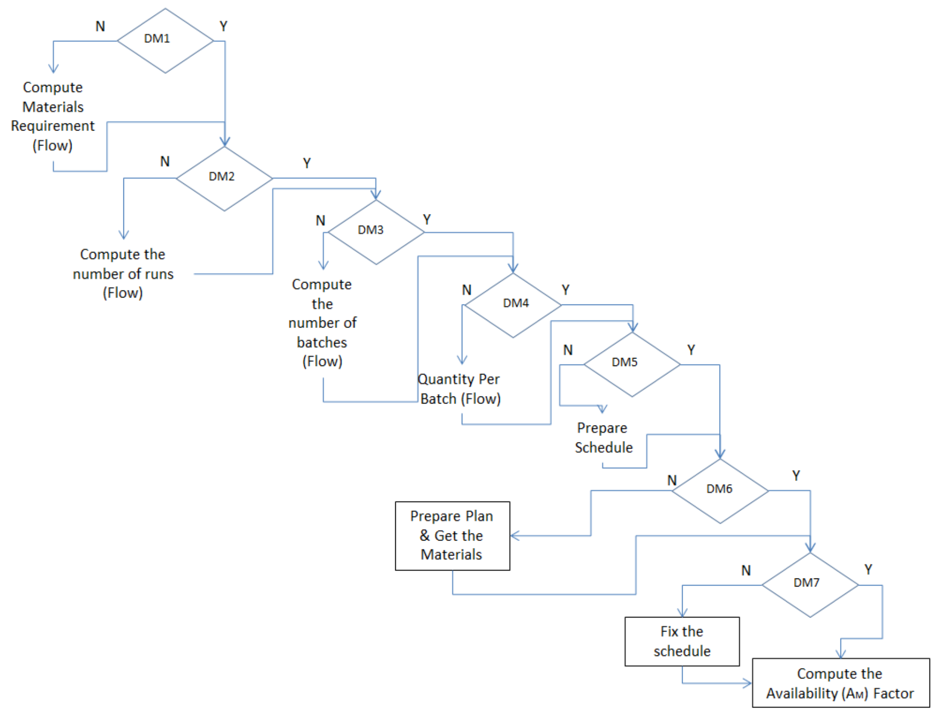


Figure A.16 Materials Disruptions Algorithm

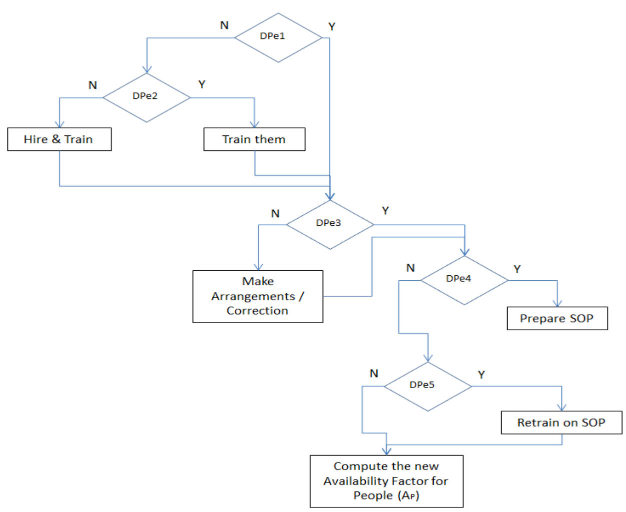


Figure A.17 People Disruptions Algorithm

A discussion about cut and path vectors is given here. "A path vector, $\underline{x}$, is a component status vector for which the corresponding system status function has a value of 1. A minimum path vector, $\underline{x}$, is a path vector for which any vector y<$\underline{x}$ has a corresponding system status function with a value of 0. A minimum path set, P_j, is the set of indices of a minimum path vector for which the component status variable has a value of 1. A cut vector, $\underline{x}$, is a component status vector for which the corresponding system status function has a value of 0. A minimum cut vector, $\underline{x}$, is a cut vector for which any vector y>$\underline{x}$ has a corresponding system status function with a value of 1. A minimum cut set is the set of indices of a minimum cut vector for which the component status variable has a value of 0. A minimal path is a set of components that comprise a path, but the removal of any one component will cause the resulting set to not be a path. If any one of the components in the minimal path subsequently fails, the system will fail. A cut is a set of components such that if all the components in the cut fail, while all other components are successful, the system will fail. The minimal cut is a set of components that comprise a cut, but the removal of any one component from the set causes the resulting set to not be a cut. [79]".

Example of TF computation for Phase 4: For a system with no variation, the values of the coefficient of variation are assumed to be zero. Assuming the values of A_E, A_S, A_M, A_P as 0.95, 0.99, 0.99, and 0.99 respectively will result in an availability factor of 0.922. For validation the values are obtained from the facility information. By applying these values to Equation 3.18, the TF_D is computed as 169.4779 which is more than the TF_V; implying that this system has more effect of disruption than variation with the assumed values.

Phase 5 – Additional Flow Design Algorithms

The detailed logic of arriving at the solutions and some of the decisions to be made are discussed here. Capacity Analysis in Figure A.21 considers the capacity of the plant and the capacity of the individual stations. It identifies whether the system is automated or manual or semi-automated and assesses the equipment needed. Since the product is normally designed by the company, the detailed information will be available with the company. If it is not available, then it can be obtained either by developing the prototype of the product and by testing it or by reverse engineering the product by the competitor (if it is legally acceptable). The algorithms for flow design not discussed in Chapter 4 are presented in this appendix. The notations or nomenclature for the algorithms are given in Table 15. Some additional information is given in Table 16.

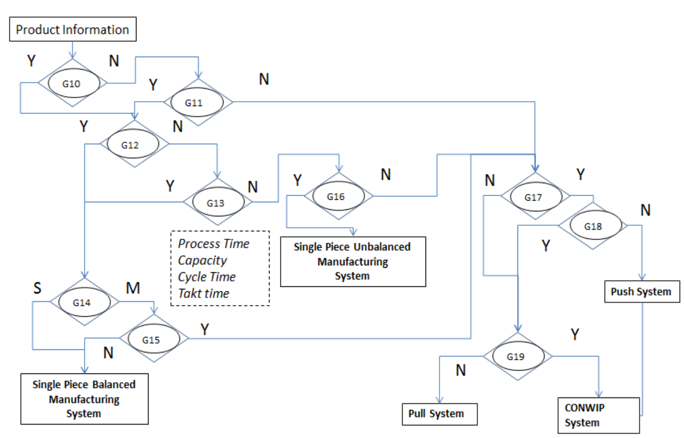


Figure A.18 Flow Selection

Table 13 Notations for Flow Selection Algorithm of Figure A.18

Main module	**Sub Module**	**Variables / Notation**	**Decision Rule / Condition**
Flow Analysis	Flow Type Selection	G10	Is the product consumed in single units?
		G11	Can the product be of single unit consumption?
		G12	Are the processes balanced?
		G13	Can the processes be balanced?
		G14	Processing capacity of stations?
		G15	Is the processing time same for single and multiple units?
		G16	Is single unit processing time same as multiple units?
		G17	Are there bottleneck processes?
		G18	Can the bottleneck issues be fixed?
		G19	Does the system require a particular WIP to be kept always in the system?

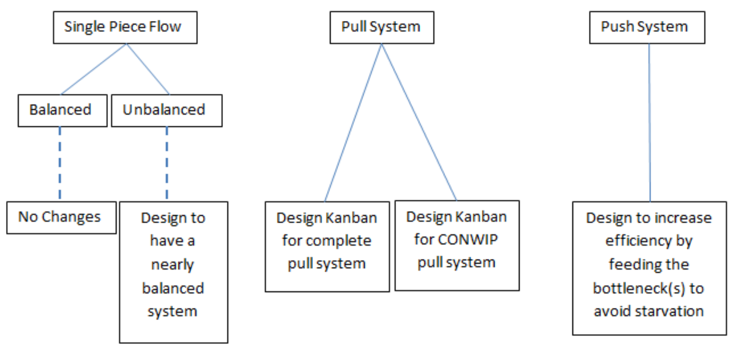


Figure A.19 Design Type

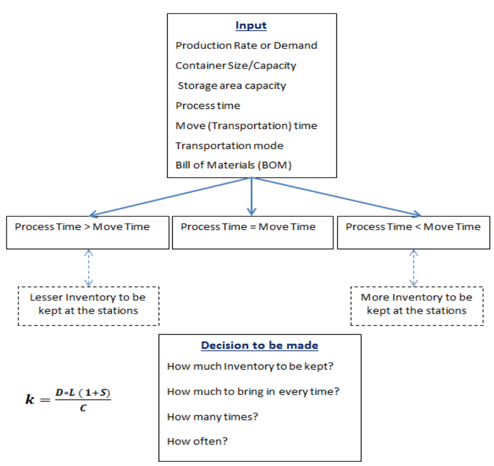


Figure A.20 Inventory Decision

Table 14 Discussion about Inventory

Case	Condition	Inventory at the process
1	Process Time > Move Time	Inventory level in front of the process should be less
2	Process Time = Move Time	Introduce WIP one by one to the process if the material movement is automated by a conveyor.
3	Process Time< Move Time	Inventory level in front of the process should be more

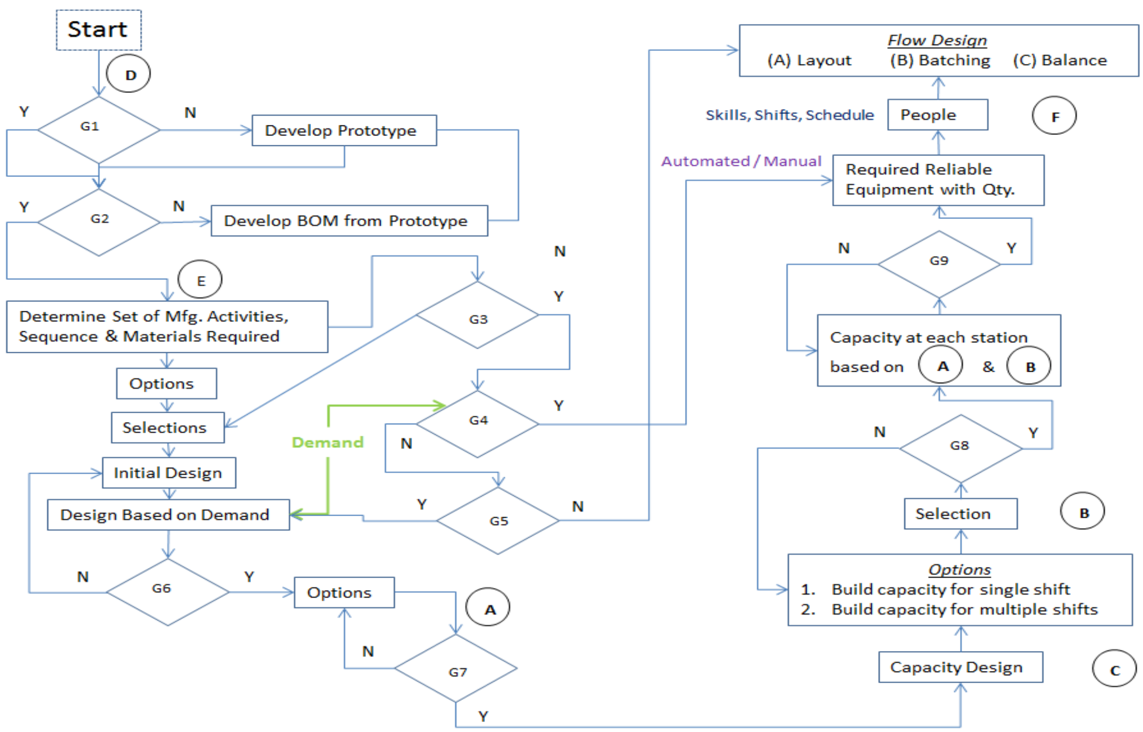


Figure A.21 Capacity Analysis

Table 15 Nomenclature for flow design algorithm

Main module	Sub Module	Factors	Variables / Notation	Decision Rule / Condition
Model Design Inputs			Demand (Y), $t_1, t_2, \dots t_n$	
Prerequisites for design			G1	Is product design available?
			G2	Is BOM available?
			G3	Does Manufacturing Capability exist?
Capacity Determination	Theoretical Capacity determination	TF, TA $t_1, t_2, \dots, t_n$	G4	Does the capacity meet demand? If TF ≤ TA, then capacity meets demand
			G5	Can changes be made to the physical infrastructure?
	Practical Capacity determination	TF, TA	G6	Does the design meet demand? If TF ≤ TA, then capacity meets demand
			G7	Accept the design?
			G8	Accept the capacity selection?
			G9	Accept the new capacity design?
Flow Analysis	Flow Type Review		F31	Combination of Push and Pull Systems
			F32	Combination of Push and CONWIP
			F33	Push System
Design Changes				
Design for Flow	Flow Planning		FP1	Single Product (S) or Multiple Products (M)?
			FP2	How many Product Families?
			FP3	Is there more than one path in the production?
			FP4	Are there bottlenecks in the paths?
			FP5	Can the bottlenecks be fixed?
	Work Environment Preparation		WEP1	Is the work area properly prepared?
			WEP2	Are the updates acceptable?
			WEP21	Which of the criteria are applicable?
			WEP22	Which of the sub-criteria are needed?
	Process Stabilization by Standardizing Work		PSSW1	Is the work standardized?
			PSSW2	Is the work standardization complete?
	Prerequisites for Flow		PFF1	Is complete information available and shared?
			PFF2	Is information availability and sharing issues fixed?

Table 15. Continued.

Main module	Sub Module	Factors	Variables / Notation	Decision Rule / Condition
Design for Flow (contd.)			PFF3	Is equipment available when needed?
			PFF4	Are equipment availability issues fixed?
			PFF5	Are materials available when needed?
			PFF6	Are material availability issues fixed?
			PFF7	Are trained people available when needed?
			PFF8	Are personnel availability issues fixed?
	Batching		BAT1	Single Piece Production (0) or Batch production (1)?
			BAT2	Fixed (0) or Random (1) Batch Size?
			BAT3	Batch Size? Small (0) or Large (1)?
			BAT4	Range of batch size? ((0 = 1 to Mid-Level; 1 = Mid-Level to Max))
			BAT5	Accept batch size selection? (0= No; 1 = Yes)
			BAT6	Accept TF? (0 = No; 1 = Yes)
			BAT7	Set-Up Reduction
	Balancing		BAL1	Is the takt time available?
			BAL2	Is CT available?
			BAL3	Is CT < takt time?
	Balancing (contd.)		BAL4	Can CT be reduced?
			BAL5	Is CT < takt time?
			BAL6	Is the system machine based (0) or people based (1)?
			BAL7	Can the number of skilled and trained people increased?
			BAL8	Can the number of machines be added, or the efficiency increased?
			BAL9	Is the change acceptable?
			BAL10	Is CT <takt time?
	Level Scheduling to Process Capacity		LO1	Are physical changes possible?
			LO2	Is cell design possible?
Any additional Factors to be considered?				

Table 16 Additional Information to Develop Operations Management

Main module	Sub Module	Factors	Variables / Notation	Decision / Values
Operational Management	Equipment	Quantity	Q_i	How many?
		Capacity	TC, PC	Theoretical and Practical
		Availability	A	tf and tr
		Reliability	r_p, $r_{s\ or}\ r_{sp}$	Effective reliability of the system (parallel, series or combination)
				Number of breakdown events
				Actual Operating Time
				Downtime of machine(s)
				Failure rate
	Material			Right Quantity (%)
				Right Quality (%)
	People			How many?
				Shifts
				Development Plans
				Skill set
				Absenteeism
				Schedule
	Schedule			Total Scheduled time (Process, maintenance), Overtime?

From the product design, the information available will be used to prepare the bill of materials (BOM) for that specific product. The manufacturing activities and its sequence should be available from the product characteristics and the BOM which will determine how it is to be manufactured. It will lead to check whether the manufacturing capability exists or not. If it doesn't exist, the initial design is to be developed and combined with demand to determine the options for product manufacturing. If the manufacturing capability exists, the product design/characteristics, combined with the quantity to be produced (demand), will give enough information about the options for the product manufacturing. The demand for the product will normally be driven by the customer request or from the marketing department. The demand has to be known fairly accurately because the system is to be designed to meet the demand. If the demand is not known, then the facility is to be designed with a planned capacity, which the management identifies as the quantity which the company will be able to sell. This drives the initial idea regarding the different options about each cell /production area for each stage starting from the final product working backwards until the first stage for that particular manufacturer is reached.

The next important step is to establish the capacity of the plant. The manufacturing plant capacity is to be decided carefully because once the plant is put together it is not easy to change. Deciding on whether to make to stock or make to order depends on the type of manufacturing and its characteristics. If it is a make to order, then the capacity of the plant depends on the customer demand and the duration of the contract (unless it is a small machine shop where jobs are created/ acquired based on personal connection or some other marketing strategy). For the purpose of this dissertation, it is assumed the customer exists and the demand is known and will be for the long term. The plant capacity will be dependent on the actual process times at each station. Therefore, an important input to determine the capacity is the processing time and the demand itself. The material required to produce the quantity demanded is calculated. The schedule and quantity are connected to the capacity of the plant itself and the schedule of its operations. The total material requirement will be the quantity of product to be manufactured (Y) multiplied by the quantity for one product for each part. If there are yield issues in the line, the material requirement will have to be adjusted for those issues.

Once the capacity of the plant is determined, the next step is to determine the equipment/machine needed and its layout. This dissertation is constrained by the fact that changes cannot be made to the physical system and hence the available layout is assumed to be operational. If it is an entirely manual operation, then only the tools which aid the operations are needed. The processing time at each step is a determinant of whether automation is needed or not. If the processing time is in seconds or less, then automation is the only feasible way. The layout depends on: 1) the product manufacturing, (i.e., whether it is in sequential or parallel or a combination) and should also connect back to the initial idea about options to manufacture. 2) Will there be more than one line; how much a single line can produce, will determine the number of production lines. 3) Also, to be determined is the type of production flow (single piece flow or batch production). This in turn depends on the type of product and the capacity of the workstation. Furthermore, the factors related to the operational aspects of the schedule of the plant should also be considered. Organizations can develop their own schedule considering the factors impacting their operations.

Once the layout and capacity are decided, the next important decision is about the people/personnel involved in the operation. The following considerations determine the input into this aspect. Are the operations automated / manual? What the ratio is between automated to manual operation? The schedules of operations are determined at the layout level. There should be a match between the skills of the personnel selected and the requirement of the job. Training is an important factor to be considered. Some of the operations may require a cross- trained flexible work force. For some of the industries, there will be a regulatory requirement for people to be present, even though the system is completely automated. If the operations entail 24/7 operations or night work, that is another consideration to be made. It depends on the processing time at each station; if the processing time is in weeks or months and if it is to be a continuous operation, then 24/7 operations will be necessary. Supermarkets are used in manufacturing systems. Some of the important parameters to be considered in the establishment of supermarkets are: Location(s), Maximum quantity, Safety Stock, Reorder point, Order quantity, Quantity to be released each time (batch size) and Minimum quantity.

The detailed block diagrams for the individual components in the main block diagram of Design for Flow (Section 3.7) is shown from Figure A.22 to Figure A.25. The flowcharts for these blocks are given in Figure A.26 to Figure A.29. The flow charts for batching are given in Figure A.30 and Figure A.31 whereas the flowcharts for balancing are given in Figure A. 32 and Figure A.34. Layout flowchart is in Figure A.35 and the flow chart for system level flow arrangement is in Figure A.36.

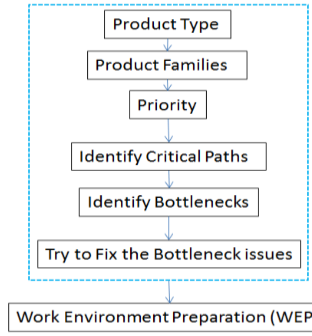


Figure A.22 Flow Planning block diagram

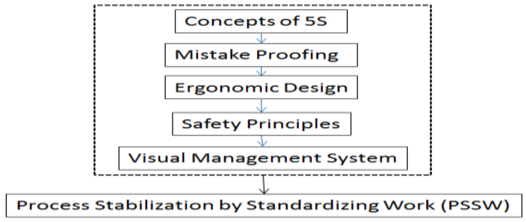


Figure A.23 Work Environment Preparation block diagram

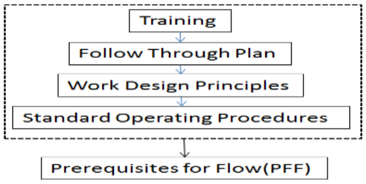


Figure A.24 PSSW block diagram

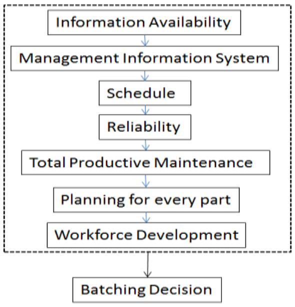


Figure A.25 PFF block diagram

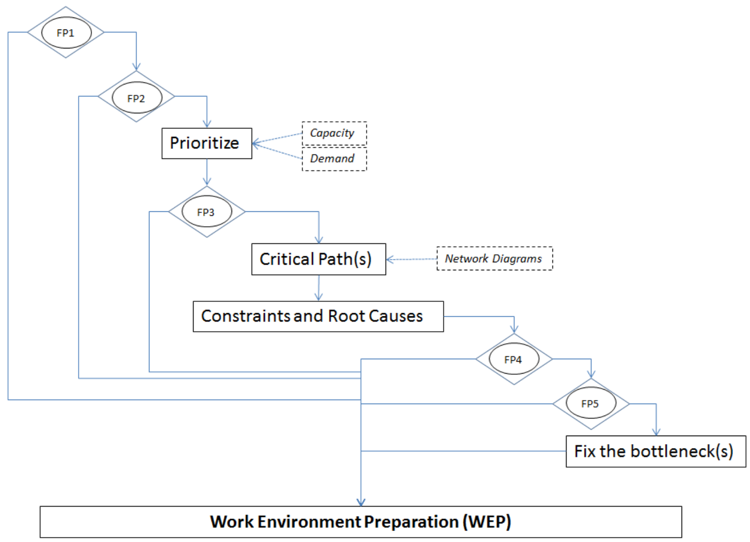


Figure A.26 FAD1 Flow Planning

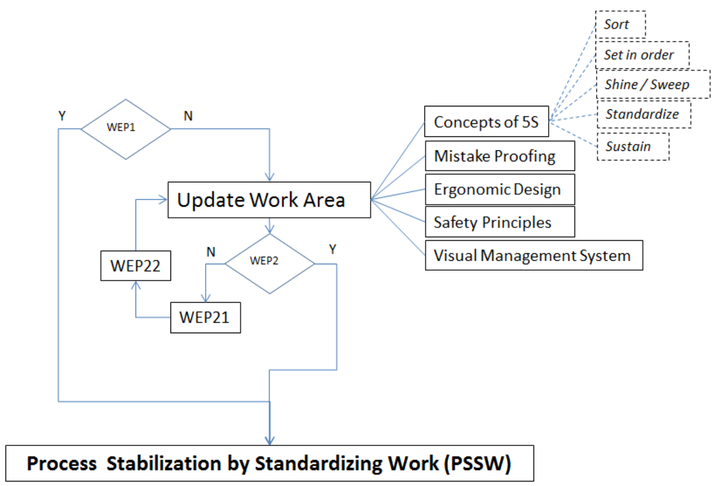


Figure A.27 FAD2 WEP

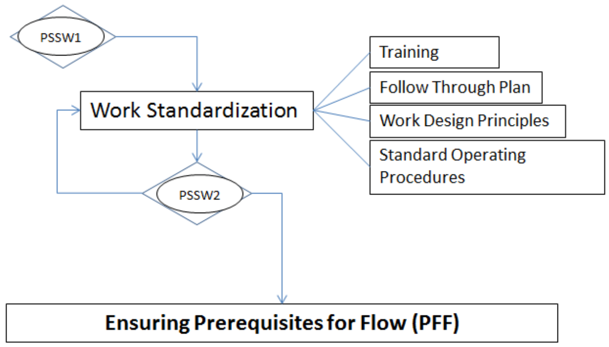


Figure A.28 FAD3 PSSW

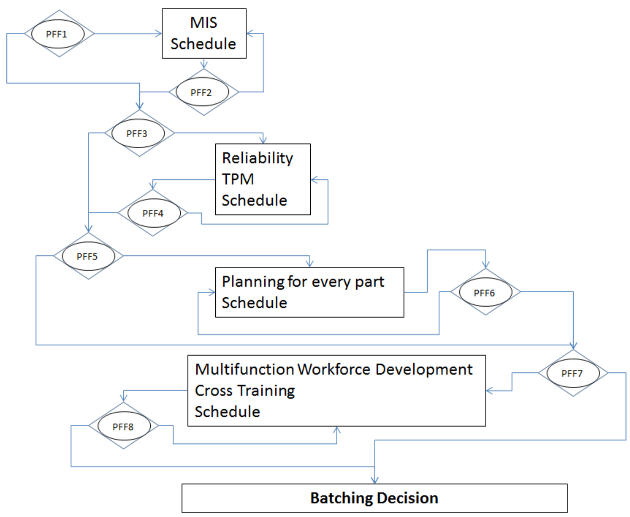


Figure A.29 FAD4 PFF

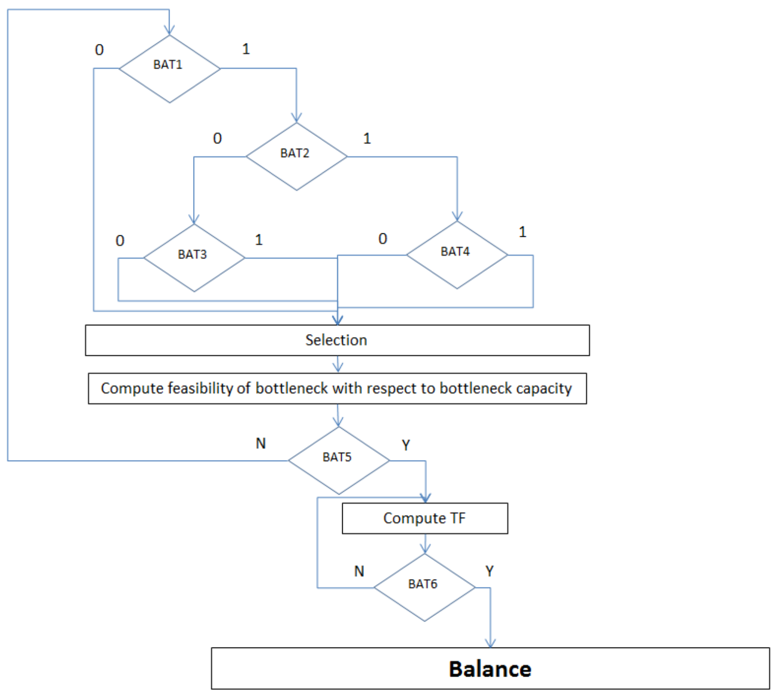


Figure A.30 Batching FAD5 part 1

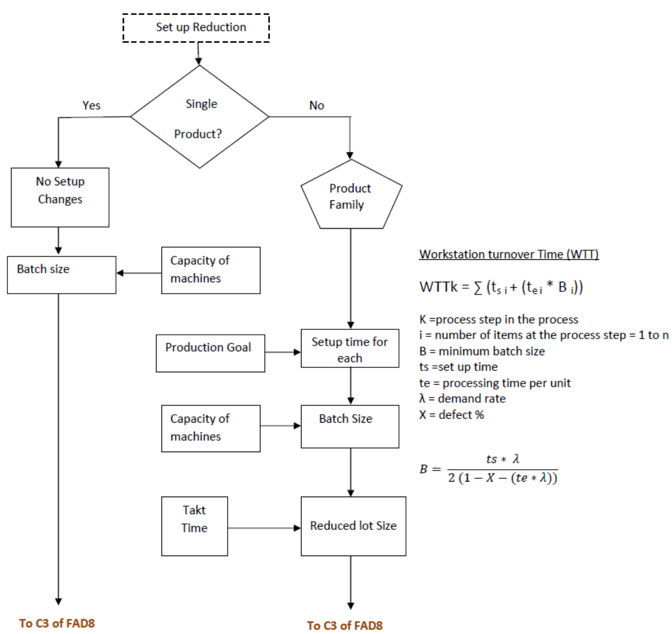


Figure A.31 Batching FAD5 part 2 set up reduction

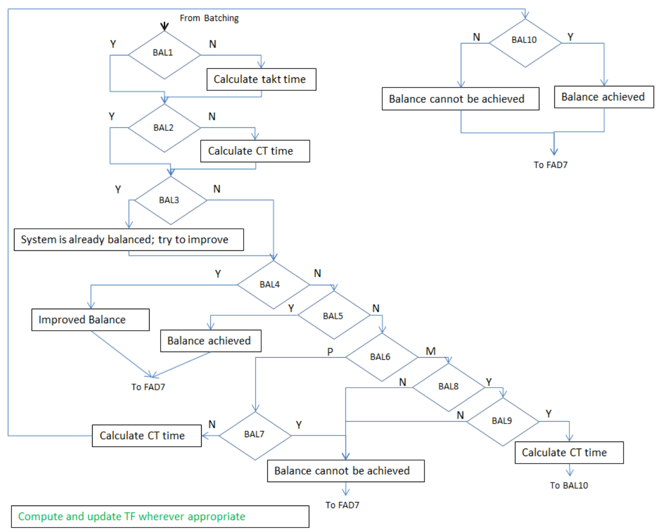


Figure A. 32 FAD6 Balancing part 1

A short discussion about balancing is given here. A production line, as shown in Figure A. 33 is considered as an example. The effective processing times are 7, 6, 42 and 21 units respectively for Pr_1 to Pr_4. This is an unbalanced system. In a push system, there will be an accumulation of 5 units at the input of Pr3 the first time a unit is processed at that station. The inventory will keep on increasing if unchecked. Other processes will not have accumulating inventory. This system can be converted to be one with efficiency in many ways. One way is to introduce material to Pr1 at the beginning and then in the interval of 42 units of time. Another way is to process 6 units (batch) at the beginning and then process another 6 units starting at 252 units of time (batch processing of 6 units at Pr1 starts every (42 x 6) units of time (t3 · batch size (b))). This way the maximum inventory at Pr3 will be limited to 5. Another way is to have random batch sizes between 2 and 5 introduced every (t3 · b) units of time.

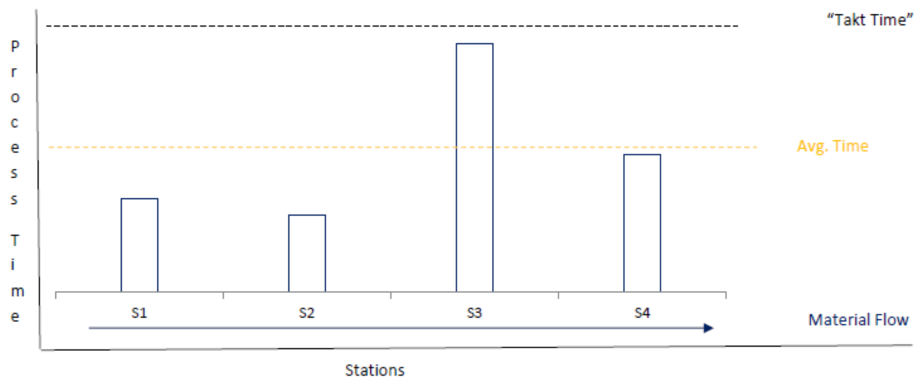
Figure A. 33 Example of a linear production line

Balance Design

Perfect balance occurs only when the processing time and the rate of production ($r_e = \frac{m}{t_e}$) of all the stations in the line are equal or when all stations have equal capacity. Perfection is far away from reality. Balance is obtained by making sure that the cycle time of all the line is less than the takt time (t_{tkt} > CT) by employing appropriate actions such as adding another machine(s) or more people or improving the process.

$$Takt\ time = \frac{time\ available\ during\ the\ period}{demand\ to\ be\ met\ during\ the\ period}$$

Takt time is defined as the time interval between outputs. It is the rate at which a finished product needs to be completed in order to meet customer demand. It should be greater than CT. In a balanced line, the processing time of all the stations should be less than its takt time. If there are four stations (S_1, S_2, S_3, S_4) that are sequential in the line and if their effective process times are t_1, t_2, t_3, t_4 respectively, then CT = $t_1 + t_2 + t_3 + t_4$. Perfect balance occurs when $t_1=t_2=t_3=t_4$ and CT≤ takt time and when the capacity of all the stations are the same.



A measure of importance is the difference between the takt time and the processing time of each station. Another is the difference between the average time of the line and the processing time of individual stations.

The work in process (WIP) kept between stations plays an important role in the balance. Hence the inventory system design is another important factor to be considered. It depends on the type of production system; push, pull or a combination of both.

To FAD7

Figure A.34 FAD6 Balancing part 2

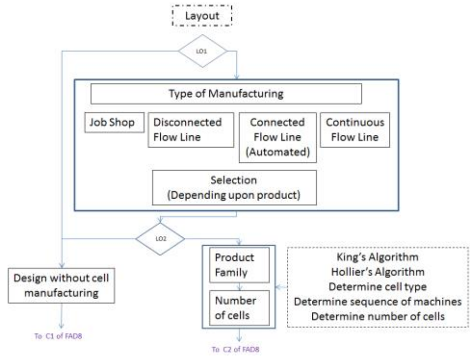


Figure A.35 FAD7

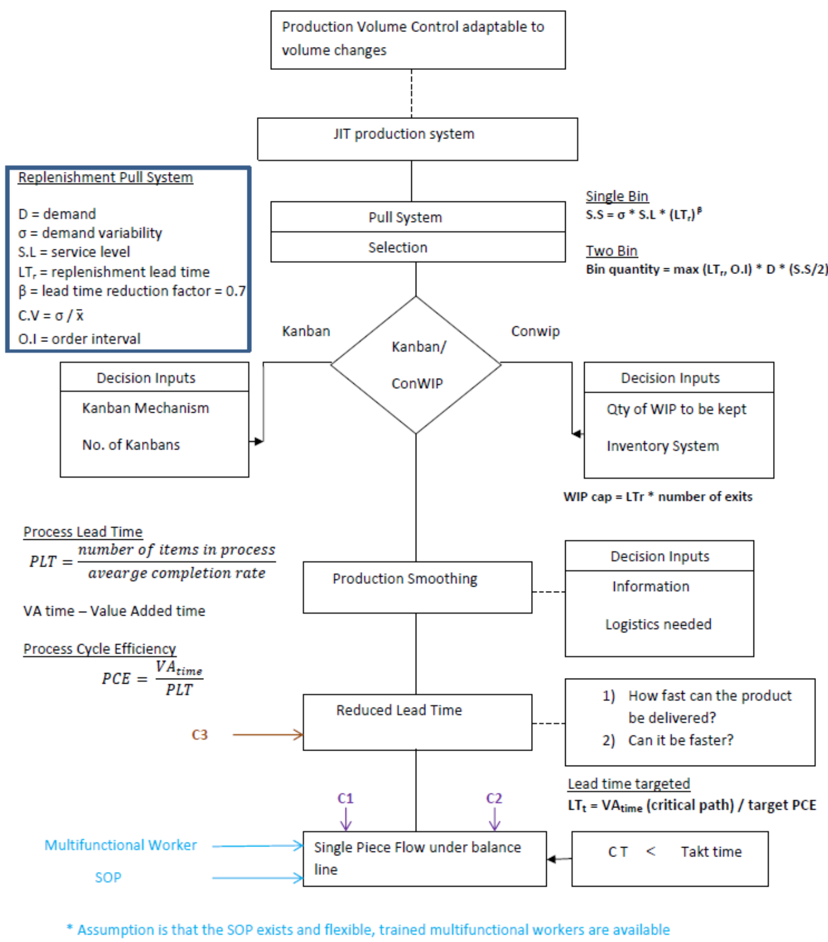


Figure A.36 FAD8

To improve push system efficiency, either a combination of push and CONWIP or a combination of push and pull (F31 or F32 in Figure A.37) can be used. The notations for this algorithm are in Table 17. The bottleneck process is identified to allow that process is fed avoiding starvation at that station. The bottleneck process will control the flow. Materials can be pushed up to the bottleneck process and kept in an inventory just before the bottleneck location. The bottleneck process will pull materials from the inventory when needed. An inventory location, after the bottleneck process, will also be useful to avoid problems down the line. Check whether the new arrangement leads any other process to become a bottleneck and if so, continue the process of feeding the new bottleneck by adding more inventory locations. One or more supermarkets may be needed. After the flow type is identified and flow design is complete, a review is to be done regarding its acceptance.

Table 17 Notations for Figure A.37

Main module	**Sub Module**	**Variables / Notation**	**Decision Rule / Condition**
Flow Analysis	Flow Type Review	F1	Is Single Piece Flow Possible?
		F11	Is it balanced?
		F2	Is Batched Pull System Possible
		F21	Is Pure Pull Possible?
		F22	Is Generic Pull System Possible?
		F23	Is Replenishment Pull System (RPS) Possible?
		F24	Single bin (0) or multi bins (1)?
		F3	Is CONWIP Possible?

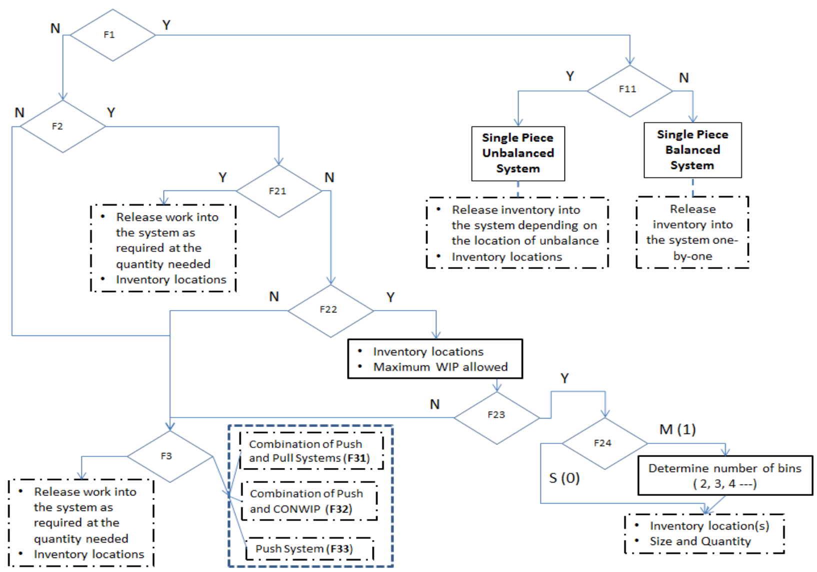


Figure A.37 Flow Type Selection (F)

Review of the Designed System

Once a particular manufacturers' system design is complete, it is analyzed and reviewed for acceptance. If not acceptable, the design is to be redone from the beginning until an acceptable design is reached. Once all the stages (classification, variation, disruption and flow) for that manufacturer are designed, the completed manufacturing system is reviewed, and corrections are to be made as needed. All the stages are to be reviewed together; checking for any issues related to balance in the system put together. Any issues discovered need to be fixed before proceeding any further. When all these are established, the system is ready to be put in place for the ideal case in the case of that manufacturer. If accepted, proceed to the previous manufacturer in the chain and repeat the processes for that particular manufacturer. The design for the previous manufacturer is to be carried out based on the design for the last manufacturer in the chain. Repeat the procedure for all the manufacturers in the chain until the supplier of the basic raw material is reached. The design from the downstream manufacturer drives the design for upstream manufacturers. The main raw material input to the downstream manufacturer is the output product of the upstream manufacturer. The upstream stages of manufacturing are dependent on the decisions the downstream stage takes. Hence, it is essential that the last stage on the manufacturing chain is designed properly. And all the stages should be designed completely in sync with others in the chain. After the design for all the manufacturers are completed, a system-wide review is to be conducted to check the viability of the design. The review steps are shown in Figure A.38 where FIN1 means 'Is the design for the manufacturer acceptable?' and FIN2 is the notation for 'Is the Total Time for the whole chain acceptable?'

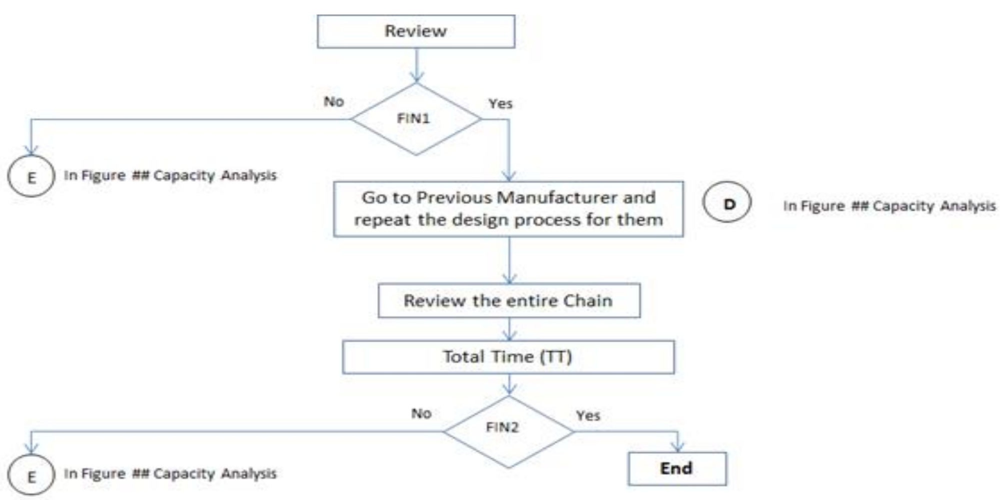


Figure A.38 Final Stages of Algorithm

Ideal cases seldom occur as there will be variations and disruptions in the real systems. So, the system should be designed to absorb / withstand the operational variations and disruptions (as discussed in phases 3 and 4). From an organizational level, the types of variability are in demand, manufacturing and the supplier. Manufacturing variability can be reduced by focusing on setup reduction, standardizing work practices, total quality management, error proofing, total preventive maintenance, flow-smoothing techniques, and by having buffers. Supplier variability can be reduced by cultivating a close working relationship with them to always be in the loop when it comes to the schedule, quantity and quality of the materials.

Appendix B – List of Distributions

Table 18 Table of Common Discrete Distributions ([71] [72] and [84])

distribution	pmf	mean	variance	mgf/moment
Bernoulli(p)	$p^x(1-p)^{1-x};\ x=0,1;\ p\in(0,1)$	p	$p(1-p)$	$(1-p)+pe^t$
Beta-binomial(n,α,β)	$\binom{n}{x}\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\frac{\Gamma(x+\alpha)\Gamma(n-x+\beta)}{\Gamma(\alpha+\beta+n)}$	$\frac{n\alpha}{\alpha+\beta}$	$\frac{n\alpha\beta}{(\alpha+\beta)^2}$	
Notes: If $X\|P$ is binomial (n,P) and P is beta(α,β), then X is beta-binomial(n,α,β).				
Binomial(n,p)	$\binom{n}{x}p^x(1-p)^{n-x};\ x=1,\ldots,n$	np	$np(1-p)$	$[(1-p)+pe^t]^n$
Discrete Uniform(N)	$\frac{1}{N};\ x=1,\ldots,N$	$\frac{N+1}{2}$	$\frac{(N+1)(N-1)}{12}$	$\frac{1}{N}\sum_{i=1}^{N}e^{it}$
Geometric(p)	$p(1-p)^{x-1};\ p\in(0,1)$	$\frac{1}{p}$	$\frac{1-p}{p^2}$	$\frac{pe^t}{1-(1-p)e^t}$
Note: $Y=X-1$ is negative binomial$(1,p)$. The distribution is *memoryless*: $P(X>s\|X>t)=P(X>s-t)$.				
Hypergeometric(N,M,K)	$\frac{\binom{M}{x}\binom{N-M}{K-x}}{\binom{N}{K}};\ x=1,\ldots,K$	$\frac{KM}{N}$	$\frac{KM}{N}\frac{(N-M)(N-k)}{N(N-1)}$	?
	$M-(N-K)\le x\le M;\ N,M,K>0$			
Negative Binomial(r,p)	$\binom{r+x-1}{x}p^r(1-p)^x;\ p\in(0,1)$	$\frac{r(1-p)}{p}$	$\frac{r(1-p)}{p^2}$	$\left(\frac{p}{1-(1-p)e^t}\right)^r$
	$\binom{y-1}{r-1}p^r(1-p)^{y-r};\ Y=X+r$			
Poisson(λ)	$\frac{e^{-\lambda}\lambda^x}{x!};\ \lambda\ge 0$	λ	λ	$e^{\lambda(e^t-1)}$
Notes: If Y is gamma(α,β), X is Poisson$(\frac{x}{\beta})$, and α is an integer, then $P(X\ge\alpha)=P(Y\le y)$.				

Table 19 Table of Common Continuous Distributions ([71],[72], [84])

distribution	pdf	mean	variance	mgf/moment
Beta(α,β)	$\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}x^{\alpha-1}(1-x)^{\beta-1};\ x\in(0,1),\ \alpha,\beta>0$	$\frac{\alpha}{\alpha+\beta}$	$\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$	$1+\sum_{k=1}^{\infty}\left(\prod_{r=0}^{k-1}\frac{\alpha+r}{\alpha+\beta+r}\right)\frac{t^k}{k!}$
Cauchy(θ,σ)	$\frac{1}{\pi\sigma}\frac{1}{1+(\frac{x-\theta}{\sigma})^2};\ \sigma>0$	does not exist	does not exist	does not exist
Notes: Special case of Students's t with 1 degree of freedom. Also, if X,Y are iid $N(0,1)$, $\frac{X}{Y}$ is Cauchy				
χ^2_p	$\frac{1}{\Gamma(\frac{p}{2})2^{\frac{p}{2}}}x^{\frac{p}{2}-1}e^{-\frac{x}{2}};\ x>0,\ p\in N$	p	$2p$	$\left(\frac{1}{1-2t}\right)^{\frac{p}{2}},\ t<\frac{1}{2}$
Notes: Gamma$(\frac{p}{2},2)$.				
Double Exponential(μ,σ)	$\frac{1}{2\sigma}e^{-\frac{\lvert x-\mu\rvert}{\sigma}};\ \sigma>0$	μ	$2\sigma^2$	$\frac{e^{\mu t}}{1-(\sigma t)^2}$
Exponential(θ)	$\frac{1}{\theta}e^{-\frac{x}{\theta}};\ x\geq 0,\ \theta>0$	θ	θ^2	$\frac{1}{1-\theta t},\ t<\frac{1}{\theta}$
Notes: Gamma$(1,\theta)$. Memoryless. $Y=X^{\frac{1}{\gamma}}$ is *Weibull*. $Y=\sqrt{\frac{2X}{\beta}}$ is *Rayleigh*. $Y=\alpha-\gamma\log\frac{X}{\beta}$ is *Gumbel*.				
F_{ν_1,ν_2}	$\frac{\Gamma(\frac{\nu_1+\nu_2}{2})}{\Gamma(\frac{\nu_1}{2})\Gamma(\frac{\nu_2}{2})}\left(\frac{\nu_1}{\nu_2}\right)^{\frac{\nu_1}{2}}\frac{x^{\frac{\nu_1-2}{2}}}{\left(1+(\frac{\nu_1}{\nu_2})x\right)^{\frac{\nu_1+\nu_2}{2}}};\ x>0$	$\frac{\nu_2}{\nu_2-2},\ \nu_2>2$	$2(\frac{\nu_2}{\nu_2-2})^2\frac{\nu_1+\nu_2-2}{\nu_1(\nu_2-4)},\ \nu_2>4$	$EX^n=\frac{\Gamma(\frac{\nu_1+2n}{2})\Gamma(\frac{\nu_2-2n}{2})}{\Gamma(\frac{\nu_1}{2})\Gamma(\frac{\nu_2}{2})}\left(\frac{\nu_2}{\nu_1}\right)^n,\ n<\frac{\nu_2}{2}$
Notes: $F_{\nu_1,\nu_2}=\frac{\chi^2_{\nu_1}/\nu_1}{\chi^2_{\nu_2}/\nu_2}$, where the χ^2s are independent. $F_{1,\nu}=t^2_\nu$.				
Gamma(α,β)	$\frac{1}{\Gamma(\alpha)\beta^\alpha}x^{\alpha-1}e^{-\frac{x}{\beta}};\ x>0,\ \alpha,\beta>0$	$\alpha\beta$	$\alpha\beta^2$	$\left(\frac{1}{1-\beta t}\right)^{\alpha},\ t<\frac{1}{\beta}$
Notes: Some special cases are exponential $(\alpha=1)$ and χ^2 $(\alpha=\frac{p}{2},\beta=2)$. If $\alpha=\frac{2}{3}$, $Y=\sqrt{\frac{X}{\beta}}$ is *Maxwell*. $Y=\frac{1}{X}$ is *inverted gamma*.				
Logistic(μ,β)	$\frac{1}{\beta}\frac{e^{-\frac{x-\mu}{\beta}}}{\left[1+e^{-\frac{x-\mu}{\beta}}\right]^2};\ \beta>0$	μ	$\frac{\pi^2\beta^2}{3}$	$e^{\mu t}\Gamma(1+\beta t),\ \lvert t\rvert<\frac{1}{\beta}$
Notes: The cdf is $F(x\mid\mu,\beta)=\frac{1}{1+e^{-\frac{x-\mu}{\beta}}}$.				
Lognormal(μ,σ^2)	$\frac{1}{\sqrt{2\pi}\sigma}\frac{1}{x}e^{-\frac{(\log x-\mu)^2}{2\sigma^2}};\ x>0,\sigma>0$	$e^{\mu+\frac{\sigma^2}{2}}$	$e^{2(\mu+\sigma^2)}-e^{2\mu+\sigma^2}$	$EX^n=e^{n\mu+\frac{n^2\sigma^2}{2}}$
Normal(μ,σ^2)	$\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(x-\mu)^2}{2\sigma^2}};\ \sigma>0$	μ	σ^2	$e^{\mu t+\frac{\sigma^2t^2}{2}}$
Pareto(α,β)	$\frac{\beta\alpha^\beta}{x^{\beta+1}};\ x>\alpha,\ \alpha,\beta>0$	$\frac{\beta\alpha}{\beta-1},\ \beta>1$	$\frac{\beta\alpha^2}{(\beta-1)^2(\beta-2)},\ \beta>2$	does not exist
t_ν	$\frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2})}\frac{1}{\sqrt{\nu\pi}}\frac{1}{(1+\frac{x^2}{\nu})^{\frac{\nu+1}{2}}}$	$0,\ \nu>1$	$\frac{\nu}{\nu-2},\nu>2$	$EX^n=\frac{\Gamma(\frac{\nu+1}{2})\Gamma(\nu-\frac{n}{2})}{\sqrt{\pi}\Gamma(\frac{\nu}{2})}\nu^{\frac{n}{2}},\ n$ even
Notes: $t^2_\nu=F_{1,\nu}$.				
Uniform(a,b)	$\frac{1}{b-a},\ a\leq x\leq b$	$\frac{b+a}{2}$	$\frac{(b-a)^2}{12}$	$\frac{e^{bt}-e^{at}}{(b-a)t}$
Notes: If $a=0,\ b=1$, this is special case of beta $(\alpha=\beta=1)$.				
Weibull(γ,β)	$\frac{\gamma}{\beta}x^{\gamma-1}e^{-\frac{x^\gamma}{\beta}};\ x>0,\ \gamma,\beta>0$	$\beta^{\frac{1}{\gamma}}\Gamma(1+\frac{1}{\gamma})$	$\beta^{\frac{2}{\gamma}}\left[\Gamma(1+\frac{2}{\gamma})-\Gamma^2(1+\frac{1}{\gamma})\right]$	$EX^n=\beta^{\frac{n}{\gamma}}\Gamma(1+\frac{n}{\gamma})$
Notes: The mgf only exists for $\gamma\geq 1$.				

Table 20 CV of a Few Common Distributions

Distribution	**Mean**	**Variance**	**Coefficient of Variation (SD / Mean)**
Normal	$\frac{1}{n}\sum_{i=1}^{n} x_i$	$\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2$	$\frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2}}{\frac{1}{n}\sum_{i=1}^{n} x_i}$
Triangular	$\frac{a+b+c}{3}$	$\frac{a^2+b^2+c^2-ab-ac-bc}{18}$	$\sqrt{\frac{(a^2+b^2+c^2-ab-ac-bc\ )}{2*\ (a^2\ +\ b^2\ +c^2\ +\ 2\mathrm{ab}\ +\ 2\mathrm{bc}\ +\ 2\mathrm{ca})}}$
Uniform	$\frac{a+b}{2}$	$\frac{(b-a)^2}{12}$	$\frac{b-a}{\sqrt{3}\,(b+a)}$

Table 21 Example for a Triangular Distribution

a	b	c	Mean	Coefficient of Variation
14	18	19	17	0.0635
12	14	16	14	0.0583
42	44	49	45	0.0327
21	24	30	25	0.0748

Appendix C – Sample MATLAB Codes and GUI

System Classification Algorithm (Phase 2) Sample MATLAB Code

```
function [TFi, TFideal, TFvf, TFdf, TFvdf] = System_Classification_General( )
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here


% developed by: Tomcy Thomas

clear all
clc

%
disp('--------------------------------');
disp('System_Classification_Algorithm');
disp('--------------------------------');



X2 = 4;
X3 = 3;
t1 = 17;
t2 = 14;
t3 = 45;
Y = 1500; % Demand should be met; so the output (throughtput) should be equal to demand (set TH = demand)

t4p = ((ceil(Y)/X3))*(21/300);
t4c = 4;
t4 = t4p + t4c;

if X3 < 3
TFi=  X3*X2*t1 + t2 + t3 +  t4p + t4c +((X3^2)/X2);
elseif X3>=3
TFi=  X3*X2*t1  + t2 + t3 +  t4p + t4c +((X3^3)/X2);

end
```

```
SCG1 = 1;
SCG2 = 1;
SCG3 = 1;
SCG4 = 1;
SCGtime = 0;
SCG5 = 0;
SCG6 = 0;

 u1 = (X3*X2*t1)/300;   % in a 300 day run time  utilzation of station1
 u2 = (X3 * t2)/300;
 u3 = (X3 * t3)/300;
 u4 = (X3 * t4) /300;

 TW = (((X2-1)/(2*u1)) * t1);   % TW is the Transfer Batch Wait

 CA1 = 0.25;
 CE1= 0.25;
 CE2= 0.25;
 CE3= 0.25;
 CE4 = 0.25;

CA2 = sqrt(u1^2 * CE1^2 + (1 - (u1)^2 )* (CA1)^2);   % CA2 = CD1
CA3 = sqrt(u2^2 * CE2^2 + (1 - (u2)^2 )* (CA2)^2);   % CA3 = CD2
CA4 = sqrt(u3^2 * CE3^2 + (1 - (u3)^2 )* (CA3)^2);   % CA4 = CD3

if X3 < 3
TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
SCGout = [t4, TFid, u1, u2, u3, u4 CA1 CE1 CA2 CE2 CA3 CE3 CA4 CE4];
elseif X3>=3
TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^3)/X2);
SCGout = [t4, TFid, u1, u2, u3, u4 CA1 CE1 CA2 CE2 CA3 CE3 CA4 CE4];
end

   if ~SCG1 && ~SCG2 && ~ SCG3 && ~ SCG4 && SCGtime && ~SCG5 && SCG6
      fprintf('\t\t Use CPM and Find the Critical Path.\n');
      % Insert Equations to compute the critical path
      %   Procedure for Finding the Critical Path in a Network Diagram:
         %1. Draw the network diagram.
         %2. Identify all paths in the network diagram.
         %3. Find the duration of each path.
         %4. The path with the largest duration is the critical path.
```

```
        fprintf('\t\t Look for the Critical Path and start designing from that path.\n');
        fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
        % Insert Equations to compute the production capacity of each station
        %   Procedure for Finding the Critical Path in a Network Diagram:
           %1. Average Production per unit Time for each station = Production Time / time per unit .
           %2. S1 =
           %3. S2 =
           %4. S3 =
           %5. S4 =
              % the lesser is the bottleneck station
         % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck
        fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
        fprintf('\t\t Ideal Conditions Time Known.\n');

        fprintf('\t\t Deterministic System.\n');
       [ Dis_Out ] = Disruptions_Pt1();
       fprintf('\t\t dISRUPTIONS Design Completed .... GOING TO VARIATIONS .\n');
        [Var_Out] = Variations_Pt1(SCGout);

    elseif ~SCG1 && ~SCG2 && ~ SCG3 && ~ SCG4 && ~SCGtime && ~SCG5 && SCG6
        fprintf('\t\t Use CPM and Find the Critical Path.\n');
        % Insert Equations to compute the critical path
        %   Procedure for Finding the Critical Path in a Network Diagram:
           %1. Draw the network diagram.
           %2. Identify all paths in the network diagram.
           %3. Find the duration of each path.
           %4. The path with the largest duration is the critical path.
        fprintf('\t\t Look for the Critical Path and start designing from that path.\n');
        fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
        % Insert Equations to compute the production capacity of each station
        %   Procedure for Finding the Critical Path in a Network Diagram:
           %1. Average Production per unit Time for each station = Production Time / time per unit .
           %2. S1 =
           %3. S2 =
           %4. S3 =
           %5. S4 =
```

```
          % the lesser is the bottleneck station
        % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck
       fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
       fprintf('\t\t Computing Ideal Conditions Time .\n');
       TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
       fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);

       fprintf('\t\t Deterministic System.\n');
      [ Dis_Out ] = Disruptions_Pt1();
      fprintf('\t\t dISRUPTIONS Design Completed .... GOING TO VARIATIONS .\n');
       [Var_Out] = Variations_Pt1();

   elseif   ~ SCG1 && ~SCG2 && ~ SCG3 && ~ SCG4 && ~SCGtime && ~SCG5 && ~SCG6
       fprintf('\t\t Use CPM and Find the Critical Path.\n');
       % Insert Equations to compute the critical path
       %   Procedure for Finding the Critical Path in a Network Diagram:
          %1. Draw the network diagram.
          %2. Identify all paths in the network diagram.
          %3. Find the duration of each path.
          %4. The path with the largest duration is the critical path.
       fprintf('\t\t Look for the Critical Path and start designing from that path.\n');
       fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
       % Insert Equations to compute the production capacity of each station
       %   Procedure for Finding the Critical Path in a Network Diagram:
          %1. Average Production per unit Time for each station = Production Time / time per unit .
          %2. S1 =
          %3. S2 =
          %4. S3 =
          %5. S4 =
           % the lesser is the bottleneck station
        % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck;
```

```
fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
fprintf('\t\t Computing Ideal Conditions Time .\n');
TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
fprintf('\t\t Stochastic System.\n');
[Var_Out] = Variations_Pt1(SCGout);
fprintf('\t\t Variation Design Completed .... GOING TO DISRUPTIONS .\n');
[ Dis_Out ] = Disruptions_Pt1();

elseif   ~ SCG1 && ~SCG2 && ~ SCG3 && ~ SCG4 && ~SCGtime && SCG5
fprintf('\t\t Use CPM and Find the Critical Path.\n');
% Insert Equations to compute the critical path
%   Procedure for Finding the Critical Path in a Network Diagram:
   %1. Draw the network diagram.
   %2. Identify all paths in the network diagram.
   %3. Find the duration of each path.
   %4. The path with the largest duration is the critical path.
fprintf('\t\t Look for the Critical Path and start designing from that path.\n');
fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
% Insert Equations to compute the production capacity of each station
%   Procedure for Finding the Critical Path in a Network Diagram:
   %1. Average Production per unit Time for each station = Production Time / time per unit .
   %2. S1 =
   %3. S2 =
   %4. S3 =
   %5. S4 =
     % the lesser is the bottleneck station
 % Another way to look at bottleneck station is to calculate the utilization of the stations
%          u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%          u2 = (X3 *t2)/TA;
%          u3 = (X3* t3)/TA;
%          u4 = (X3 * t4)/300;
%          highest utilzation stations could also be considred as the bottleneck
fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
fprintf('\t\t Computing Ideal Conditions Time .\n');
TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
fprintf('\t\t Bayesian System.\n');
FL1 = Flow_Pt1();
```

```
    elseif SCG1 && SCG2 && ~SCG3 && SCG4 && ~SCGtime && SCG5
      fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
      % Insert Equations to compute the production capacity of each station
      %   Procedure for Finding the Critical Path in a Network Diagram:
         %1. Average Production per unit Time for each station = Production Time / time per unit .
         %2. S1 =
         %3. S2 =
         %4. S3 =
         %5. S4 =
           % the lesser is the bottleneck station
       % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck
      fprintf('\t\t TH will be determined by the output rate of the bottleneck station .\n');
      fprintf('\t\t Computing Ideal Conditions Time .\n');
      TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
      fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);

      fprintf('\t\t Bayesian System.\n');
      FL1 = Flow_Pt1();

    elseif SCG1 && SCG2 && ~SCG3 && ~SCG4 && ~SCGtime && SCG5
      fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
      % Insert Equations to compute the production capacity of each station
      %   Procedure for Finding the Critical Path in a Network Diagram:
         %1. Average Production per unit Time for each station = Production Time / time per unit .
         %2. S1 =
         %3. S2 =
         %4. S3 =
         %5. S4 =
         % the lesser is the bottleneck station
       % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck
```

```
        fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
        fprintf('\t\t Computing Ideal Conditions Time .\n');
        TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
        fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
        fprintf('\t\t Bayesian System.\n');
        FL1 = Flow_Pt1();

    elseif SCG1 && SCG2 && ~SCG3 && SCG4 && ~SCGtime && ~SCG5 && SCG6
        fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
        % Insert Equations to compute the production capacity of each station
        %   Procedure for Finding the Critical Path in a Network Diagram:
            %1. Average Production per unit Time for each station = Production Time / time per unit .
            %2. S1 =
            %3. S2 =
            %4. S3 =
            %5. S4 =
           % the lesser is the bottleneck station
         % Another way to look at bottleneck station is to calculate the utilization of the stations
%           u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%           u2 = (X3 *t2)/TA;
%           u3 = (X3* t3)/TA;
%           u4 = (X3 * t4)/300;
%           highest utilzation stations could also be considred as the bottleneck
         fprintf('\t\t TH will be determined by the output rate of the bottleneck station .\n');
        fprintf('\t\t Computing Ideal Conditions Time .\n');
        TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
        fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);

        fprintf('\t\t Deterministic System.\n');
       [ Dis_Out ] = Disruptions_Pt1();
       fprintf('\t\t DISRUPTIONS Design Completed .... GOING TO VARIATIONS .\n');
       [Var_Out] = Variations_Pt1(SCGout);

    elseif SCG1 && SCG2 && ~SCG3 && ~SCG4 && ~SCGtime && ~SCG5 && SCG6
        fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
        % Insert Equations to compute the production capacity of each station
        %   Procedure for Finding the Critical Path in a Network Diagram:
            %1. Average Production per unit Time for each station = Production Time / time per unit .
            %2. S1 =
            %3. S2 =
            %4. S3 =
```

```
        %5. S4 =
        % the lesser is the bottleneck station
       % Another way to look at bottleneck station is to calculate the utilization of the stations
%          u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%          u2 = (X3 *t2)/TA;
%          u3 = (X3* t3)/TA;
%          u4 = (X3 * t4)/300;
%          highest utilzation stations could also be considred as the bottleneck
      fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
      fprintf('\t\t Computing Ideal Conditions Time .\n');
      TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
      fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
      fprintf('\t\t Deterministic System.\n');

     [ Dis_Out ] = Disruptions_Pt1();
     fprintf('\t\t DISRUPTIONS Design Completed .... GOING TO VARIATIONS .\n');
     [Var_Out] = Variations_Pt1(SCGout);

   elseif SCG1 && SCG2 && ~SCG3 && SCG4 && ~SCGtime && ~SCG5 && ~SCG6
      fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
      % Insert Equations to compute the production capacity of each station
      %   Procedure for Finding the Critical Path in a Network Diagram:
        %1. Average Production per unit Time for each station = Production Time / time per unit .
        %2. S1 =
        %3. S2 =
        %4. S3 =
        %5. S4 =
        % the lesser is the bottleneck station
       % Another way to look at bottleneck station is to calculate the utilization of the stations
%          u1 = (X3*B*t1)/TA;   %utilzation of station1; in a 300 day run time Ta is 300
%          u2 = (X3 *t2)/TA;
%          u3 = (X3* t3)/TA;
%          u4 = (X3 * t4)/300;
%          highest utilzation stations could also be considred as the bottleneck
      fprintf('\t\t TH will be determined by the output rate of the bottleneck station .\n');
      fprintf('\t\t Computing Ideal Conditions Time .\n');
      TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
      fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
      fprintf('\t\t Stochastic System.\n');
      [Var_Out] = Variations_Pt1(SCGout);
      fprintf('\t\t Variation Design Completed .... GOING TO DISRUPTIONS .\n');
```

```
    [ Dis_Out ] = Disruptions_Pt1();

elseif SCG1 && SCG2 && SCG3 && SCG4 && ~SCGtime && ~SCG5 && ~SCG6
    fprintf('\t\t TH will be determined by the output rate of the bottleneck station .\n');
    fprintf('\t\t Computing Ideal Conditions Time .\n');
    TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
    fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
    fprintf('\t\t Stochastic System.\n');
    [Var_Out] = Variations_Pt1(SCGout);
    fprintf('\t\t Variation Design Completed .... GOING TO DISRUPTIONS .\n');
    [ Dis_Out ] = Disruptions_Pt1();

elseif SCG1 && SCG2 && SCG3 && SCG4 && ~SCGtime && ~SCG5 && SCG6
    fprintf('\t\t TH will be determined by the output rate of the bottleneck station .\n');
    fprintf('\t\t Computing Ideal Conditions Time .\n');
    TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
    fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
     fprintf('\t\t Deterministic System.\n');
       [ Dis_Out ] = Disruptions_Pt1();
       fprintf('\t\t DISRUPTIONS Design Completed .... GOING TO VARIATIONS .\n');
       [Var_Out] = Variations_Pt1(SCGout);


elseif SCG1 && SCG2 && ~SCG3 && ~SCG4 && ~SCGtime && ~SCG5 && ~SCG6
    fprintf('\t\t Calculate the production capacity of each station to determine the bottleneck station.\n');
    % Insert Equations to compute the production capacity of each station
    %   Procedure for Finding the Critical Path in a Network Diagram:
       %1. Average Production per unit Time for each station = Production Time / time per unit .
       %2. S1 =
       %3. S2 =
       %4. S3 =
       %5. S4 =
       %if S1 == S2 == S3 == S4
          % DG4= 0;
       %else DG4 = 1;
       %end;
    fprintf('\t\t Balanced Line - No Bottleneck exists.\n');
    fprintf('\t\t Computing Ideal Conditions Time .\n');
    TFid=  (X3*(t1 + TW)) + t2 + t3 +  t4p + t4c +((X3^2)/X2);
    fprintf('\t\t Calculated Ideal Conditions Time as: %f .\n', TFid);
    fprintf('\t\t Stochastic System.\n');
```

```
        [Var_Out] = Variations_Pt1(SCGout);
        fprintf('\t\t Variation Design Completed .... GOING TO DISRUPTIONS .\n');
        [ Dis_Out ] = Disruptions_Pt1();

    end
    %DG1 = 0;
 %end
 fprintf('\t\t Variations and DISRUPTIONS Design Completed .\n');

 fprintf('\t\t Variation and Disruptions Algorithm Output are respectively: %f and %f .\n', Var_Out, Dis_Out);

 CA1 = Var_Out(1, 7);
 CE1 = Var_Out(1, 8);
 CE2 = Var_Out(1, 10);
 CE3 = Var_Out(1, 12);
 CE4 = Var_Out(1, 14);

% Dis_Out;  % this will be A = Ae * Am * Ap * As

R = 4;
B = 4;
%P = 4:  %% number of periods
TFvdfM = -1*ones(R*B, 22);
%TFvdfM = -1*ones(R*B*P, 23);
ton = 0;
toff = 0;
ts1 = 0;
tc1 = 0;
ts2 = 0;
tc2 = 0;
ts3 = 0;
tc3 = 0;
ts4 = 0;
tc4 = 0;

XTOT = 428;
index = 1;
  % XTOT = XTOT/P;
  % Ymatrix =[ 150 200 150 250 ]; % Demand for each period Y1 = 150 ..... Y4 = 250
  % TAmatrix = [ 30 40  30  50]
%for p = 1:P
```

```
 %Y = Ymatrix(p);
 %TA = TAmatrix(p)
for x3 = 1:R

    for x2 = 1:B
     x1 =ceil( XTOT /(x2 *x3));
     t4p = ((ceil(Y)/x3))*(21/300);
     t4c = 4;
     t4 = t4p + t4c;
    u1 = (17*x2*x3) /300;
    u2 = (14*x3)/300;
    u3 = (45*x3)/300;
    u4 = (t4 * x3)/300;
    TW = (((x2-1)/(2*u1)) * t1);

CA2 = sqrt(u1^2 * CE1^2 + (1 - (u1)^2 )* (CA1)^2);   % CA2 = CD1
CA3 = sqrt(u2^2 * CE2^2 + (1 - (u2)^2 )* (CA2)^2);   % CA3 = CD2
CA4 = sqrt(u3^2 * CE3^2 + (1 - (u3)^2 )* (CA3)^2);   % CA4 = CD3

if x3 < 3
 TFi=  (ton + ts1 + x3*x2*t1 + tc1 + ts1 + t2 + tc2 + ts3 + t3 +tc3 + ts4 + t4p + t4c + tc4 + toff +((x3^2)/x2));
 TFideal = ton + ts1 +(x3*(t1 + TW)) + tc1 + ts2 + t2 + tc2 + t3 +  t4p + t4c + ((x3^2)/x2);
 TFvf = ton + (ts1+ ((CA1^2 + CE1^2)/2) * ((u1/(1-u1))* t1) + (x3*(t1 + TW)) + tc1 )   +   (ts2 +(((CA2^2 + CE2^2)/2)*(u2/(1-u2))* t2) + t2 + tc2)  +  (ts3 +(((CA3^2 +
CE3^2)/2)*(u3/(1-u3))* t3) + t3 +tc3)   +  (ts4 +(((CA4^2 + CE4^2)/2)*(u4/(1-u4))* t4p) + t4p  + t4c + tc4) +((x3^2)/x2);
 TFdf =  ton +  (ts1 +x3* ( (t1/Dis_Out) + (TW/Dis_Out)) +tc1)   +   ts2 + (t2/Dis_Out) + tc2   +   ts3 +(t3/Dis_Out) + tc3   +   ts4 +(t4p/Dis_Out) + (t4c/Dis_Out) + tc4
+ ((x3^2)/x2);
 TFvdf = ton + ts1 +( ((CA1^2 + CE1^2)/2) * ((u1/(1-u1))* (t1/Dis_Out)) + (x3*( (t1/Dis_Out) + (TW/Dis_Out)) ) + tc1   +   ts2 +((((CA2^2 + CE2^2)/2)*(u2/(1-u2))*
(t2/Dis_Out)) + (t2/Dis_Out)) +tc2  +  ts3+ ((((CA3^2 + CE3^2)/2)*(u3/(1-u3))* (t3/Dis_Out)) + (t3/Dis_Out)) + tc3  +  ts4 +((((CA4^2 + CE4^2)/2)*(u4/(1-u4))*
(t4p/Dis_Out)) + (t4p/Dis_Out)  + (t4c/Dis_Out)) + tc4 + ((x3^2)/x2) )   ;

elseif x3 >= 3
 TFi=  ( ton + ts1 + x3*x2*t1 +tc1 + ts2 + t2 +tc2 + ts3+ t3 +tc3 + ts4 + t4p + t4c + tc4 +((x3^3)/x2));
 TFideal = ton + ts1 + (x3*(t1 + TW))+ tc1 + ts2 + t2 + tc2 + ts3+ t3 +tc3 + ts4 + t4p + t4c + tc4 + ((x3^3)/x2);
 TFvf = ton + ( ts1+((CA1^2 + CE1^2)/2) * ((u1/(1-u1))* t1) + (x3*(t1 + TW))+ tc1)   +   (ts2 + (((CA2^2 + CE2^2)/2)*(u2/(1-u2))* t2) + t2 + tc2)   +  (ts3+(((CA3^2 +
CE3^2)/2)*(u3/(1-u3))* t3) + t3 +tc3)   +  ( ts4 + (((CA4^2 + CE4^2)/2)*(u4/(1-u4))* t4p) + t4p  + t4c +tc4) +((x3^3)/x2);
 TFdf =  ton +  (ts1 +x3* ( (t1/Dis_Out) + (TW/Dis_Out))+ tc1 )    +   (t2/Dis_Out)   +   (t3/Dis_Out)   +   (t4p/Dis_Out)  + (t4c/Dis_Out) + ((x3^3)/x2);
 TFvdf = ton+ ts1 + (((CA1^2 + CE1^2)/2) * ((u1/(1-u1))* (t1/Dis_Out)) + (x3*( (t1/Dis_Out) + (TW/Dis_Out)) ) + tc1   +   ts2 +((((CA2^2 + CE2^2)/2)*(u2/(1-u2))*
(t2/Dis_Out)) + (t2/Dis_Out))+tc2   +  ( ts3+(((CA3^2 + CE3^2)/2)*(u3/(1-u3))* (t3/Dis_Out)) + (t3/Dis_Out)+tc3)   +  (ts4 +(((CA4^2 + CE4^2)/2)*(u4/(1-u4))*
(t4p/Dis_Out)) + (t4p/Dis_Out)  + (t4c/Dis_Out) +tc4) + ((x3^3)/x2) )   ;
```

```
end
 TFcombo = [x2 x3 x1 TFi u1 u2 u3 u4 CA1 CE1 CA2 CE2 CA3 CE3 CA4 CE4 Dis_Out TW TFideal TFvf TFdf TFvdf];
   %Replace with the line below if multiple periods are used
 % TFcombo = [p x2 x3 x1 TFi u1 u2 u3 u4 CA1 CE1 CA2 CE2 CA3 CE3 CA4 CE4 Dis_Out TW TFideal TFvf TFdf TFvdf];
 TFvdfM(index,:) = TFcombo;
  index = index + 1;

    end

 save('Sample1.mat', 'TFvdfM', 'x2', 'x3','x1', 'TFi', 'u1', 'u2', 'u3', 'u4', 'CA1', 'CE1', 'CA2', 'CE2', 'CA3', 'CE3', 'CA4', 'CE4', 'Dis_Out', 'TW', 'TFid', 'TFvf', 'TFdf',
'TFvdf'); %Comment this if using multiple periods
 %The following line only if multiple periods are used
 %save('Sample1.mat', 'TFvdfM','p', 'x2', 'x3','x1', 'TFi', 'u1', 'u2', 'u3', 'u4', 'CA1', 'CE1', 'CA2', 'CE2', 'CA3', 'CE3', 'CA4', 'CE4', 'Dis_Out', 'TW', 'TFid', 'TFvf', 'TFdf',
'TFvdf');
 Sample2 =  TFvdfM(:,:);
 xlswrite('Sample1.xlsx',Sample2)

  %Following 5 lines to be used when the TA is one continous block
  %compare3 = TFvdfM(:,3) < 50 TFvdfM(:,4) < 300 & TFvdfM(:,5) <= 1 & TFvdfM(:,6) <= 1  & TFvdfM(:,7) <= 1  & TFvdfM(:,8) <= 1  & TFvdfM(:,19) < 300 &
TFvdfM(:,20) < 300 & TFvdfM(:,21) < 300 & TFvdfM(:,22) < 300 ;
  %Selected = TFvdfM(compare3, :);
  %TFvdf_Selected = Selected(:, :);  %selects all rows and columns
  %save ('TFvdf_Selected.mat', 'TFvdf_Selected');
  %xlswrite('FinalSelection.xlsx',TFvdf_Selected);

 %The following code only if multiple periods are involbed;
 %%%compare4 = TFvdfM(:,4) < 50 TFvdfM(:,5) < (p TAmatrix(p)) & TFvdfM(:,6) <= 1 & TFvdfM(:,7) <= 1  & TFvdfM(:,8) <= 1  & TFvdfM(:,9) <= 1  & TFvdfM(:,20)
< TAp & TFvdfM(:,21) < TA & TFvdfM(:,22) < TA & TFvdfM(:,23) < TA ;
 %compare4 = TFvdfM(:,4) < 50 TFvdfM(1:R*B,5) < TA1 & TFvdfM(1+R*B:2*R*B,5) < TA2 & TFvdfM(1+(2*R*B):3*R*B,5) < TA3 & TFvdfM(:,6) <= 1 & TFvdfM(:,7)
<= 1  & TFvdfM(:,8) <= 1  & TFvdfM(:,9) <= 1  & TFvdfM(:,20) < TAp & TFvdfM(:,21) < TA & TFvdfM(:,22) < TA & TFvdfM(:,23) < TA ;
  %Selected2 = TFvdfM(compare4, :);
  %TFvdf_Selected_multiple_Periods = Selected2(:, :);  %selects all rows and columns
  %save ('TFvdf_Selected_multiple_Periods.mat', 'TFvdf_Selected_multiple_Periods');
  %xlswrite('FinalSelectionPeriods.xlsx',TFvdf_Selected_multiple_Periods);

end
end

%end
%
```

Implementation of floating bottleneck algorithm

```
FL_BN = xlsread('example3.xlsx');
[K, c] = size(FL_BN);

count_valid = 0;
count_max_stn = zeros (1, c);

for k = 1:K

    %check if not full
    if min(FL_BN (k, :)) < 0.00001
        continue;
    else
        maxval = max(FL_BN (k, :));
        idx = find(FL_BN(k,:) == maxval);
        tmp = zeros(1, c);
        tmp(idx) = 1;
        count_max_stn = count_max_stn + tmp;
        count_valid = count_valid + length(idx);
    end
end
prob_float_bottleneck = count_max_stn / count_valid;
save('Prob.mat', 'prob_float_bottleneck');
.
```

Utilization Algorithm Code

```
function [  ] = Utilization_Process_Arrival()
%UNTITLED Summary of this function goes here
%   Detailed explanation goes here

X2 = 4;
X3 = 2;
t1 = 17;
t2 = 14;
t3 = 45;
Y = 1500;
t4 = ((Y/X3)*(21/300)) + 4;
VG12 = 1;
VG14 = 1;
V6 = 1;
V7 = 1;
VG16 = 1;

if ~VG12 && ~VG14
   fprintf('\t\t Compute Utilization of stations .\n');
   % code to compute Utilization of stations
   u1 = (X3*X2*t1)/300;   % in a 300 day run time  utilzation of station1
   u2 = (X3 *t2)/300;
   u3 = (X3* t3)/300;
   u4 = (X3 * t4) /300;
   Util_Out = [u1, u2, u3, u4];
   fprintf('\t\t Deterministic System .... Go to Disruptions .\n');
   %[ Dis_Out ] = Disruptions_Pt1();

elseif ~VG12 && VG14 && V6 && V7 && VG16
   fprintf('\t\t Compute Utilization of stations .\n');
   % code to compute Utilization of stations
   u1 = (X3*X2*t1)/300;   % in a 300 day run time  utilzation of station1
   u2 = (X3 *t2)/300;
   u3 = (X3* t3)/300;
   u4 = (X3 * t4) /300;
   Util_Out = [u1, u2, u3, u4];
   fprintf('\t\t Process Dependent ... Control the process .\n');
   fprintf('\t\t Go To VG312 .\n');
   %[Var_Out] = Variations_Pt1(Util_Out);
```

```
elseif ~VG12 && VG14 && V6 && ~V7
   fprintf('\t\t Compute Utilization of stations .\n');
   % code to compute Utilization of stations
   u1 = (X3*X2*t1)/300;   % in a 300 day run time  utilzation of station1
   u2 = (X3 *t2)/300;
   u3 = (X3* t3)/300;
   u4 = (X3 * t4) /300;
   Util_Out = [u1, u2, u3, u4];
   fprintf('\t\t Arrival Dependent ... Control the arrival .\n');
   fprintf('\t\t Go To VG312 .\n');
   %[Var_Out] = Variations_Pt1(Util_Out);

elseif ~VG12 && VG14 && ~V6 && V8
   fprintf('\t\t Compute Utilization of stations .\n');
   % code to compute Utilization of stations
   u1 = (X3*X2*t1)/300;   % in a 300 day run time  utilzation of station1
   u2 = (X3 *t2)/300;
   u3 = (X3* t3)/300;
   u4 = (X3 * t4) /300;
   Util_Out = [u1, u2, u3, u4];
   fprintf('\t\t Arrival Dependent ... Control the arrival .\n');
   fprintf('\t\t Go To VG312 .\n');
   %[Var_Out] = Variations_Pt1(Util_Out);

elseif VG12 && VG14 && V6 && ~V7
   fprintf('\t\t Arrival Dependent ... Control the arrival .\n');
   fprintf('\t\t Go To VG312 .\n');

elseif VG12 && VG14 && ~V6 && V8
   fprintf('\t\t Arrival Dependent ... Control the arrival .\n');
   fprintf('\t\t Go To VG312 .\n');

elseif VG12 && VG14 && V6 && V7
   fprintf('\t\t Process Dependent ... Control the process .\n');
   fprintf('\t\t Go To VG312 .\n');

end

end
```

Variation of 4 CRs Sample MATLAB code

```
function [ Var] = Variations_4CRs(Var_IN)
disp('------------------------------------------------------------');
disp('Algorithm to Compute Variation caised by Critical Resources');
disp('------------------------------------------------------------');
fprintf('\t\t Equipment Related Variation .\n');
    [Repair] = Repair_Variation(Var_IN);

    [Ramp] = Ramping_Up_Variations(Repair);

    [SetUp_Var1] = SetUp_Variations(Ramp);

    [Qlty_Var1] = Quality_Variations(SetUp_Var1);



    fprintf('\t\t People Variation .\n');
          [Pe1]  = People_Variations(Qlty_Var1  );

    fprintf('\t\t Variation becuase of Schedule/Information Problems .\n');

        [ Sch1] = Schedule_Information_Problems(Pe1);

      fprintf('\t\t Material Variation ... After Checking For the Importance of Arrival Versus Process.\n');

          %[Var_Pt5]  = Variations_Pt5(Sch1 );
          [Var_Pt5]  = Variations_Pt5_V2(Sch1 );

         fprintf('\t\t ------ ...... Going To Placement Variation ... ------ .\n');
          [ Var_Pla] = Placement_Variations(Var_Pt5);


 Var = Var_Pla;

end

function [Repair] = Repair_Variation(Var_IN)
t4 = Var_IN(1,1);
TFi = Var_IN(1,2);
u1 = Var_IN(1,3);
u2 = Var_IN(1,4);
u3 = Var_IN(1,5);
u4 = Var_IN(1,6);
ca1 = Var_IN(1,7);
c01 = Var_IN(1,8);
```

```
ca2 = Var_IN(1,9);
c02 = Var_IN(1,10);
ca3 = Var_IN(1,11);
c03 = Var_IN(1,12);
ca4 = Var_IN(1,13);
c04 = Var_IN(1,14);
  VG10 = 0;
  VG11 = 0;

  cr1 = 0.2887;  %SD = 1.15 and Avg = 4
  cr2 = 0.2887;
  cr3 = 0.2887;
  cr4 = 0.2887;
  mr1 = 4;
  mr2 = 4;
  mr3 = 4;
  mr4 = 4;
  mf1 = 24*30*6; % 6 months in hours
  mf2 = 24*30*6;
  mf3 = 24*30*6;
  mf4 = 24*30*6;
  t01 = 17;
  t02 = 14;
  t03 = 45;
  t04 = t4;

  Ab1 = mf1/(mf1 +mr1);
  Ab2 = mf2/(mf2 +mr2);
  Ab3 = mf3/(mf3 +mr3);
  Ab4 = mf4/(mf4 +mr4);

  if ~VG10
    fprintf('\t\t List the Causes and Solutions for MTTR .\n');
    fprintf('\t\t Causes .\n');
    fprintf('\t\t Solutions .\n');
    fprintf('\t\t Improve the value of CV.\n');
    %CVp =  :


    ce1 =  sqrt (c01^2 + Ab1*(1-Ab1) *(mr1/t01) + cr1^2 * Ab1*(1-Ab1) *(mr1/t01));
    ce2 = sqrt (c02^2 + Ab2*(1-Ab2) *(mr2/t02) + cr2^2 * Ab2*(1-Ab2) *(mr2/t01));
    ce3 = sqrt (c03^2 + Ab3*(1-Ab3) *(mr3/t03) + cr3^2 * Ab3*(1-Ab3) *(mr3/t03));
    ce4 = sqrt (c04^2 + Ab4*(1-Ab4) *(mr4/t04) + cr4^2 * Ab4*(1-Ab4) *(mr4/t04));


    CV4stations = [t4 TFi u1 u2 u3 u4 ca1 ce1 ca2 ce2 ca3 ce3 ca4 ce4];
```

```
        fprintf('\t\t Compute the updated value of TF.\n');
        % Insert Code to Compute the updated value of CV
         %TF -  ;

    elseif VG10 && VG11
        fprintf('\t\t Variation is at Material, People or S/I .\n');

    elseif VG10 && ~VG11
        fprintf('\t\t List the Causes and Solutions for MTTF .\n');
        fprintf('\t\t Causes .\n');

        fprintf('\t\t Solutions .\n');
        fprintf('\t\t Improve the value of CV.\n');
        % Insert Code to Compute the updated value of CV
        %CV =  :
         fprintf('\t\t Compute the updated value of TF.\n');
        % Insert Code to Compute TF
        %TF -  ;
    end
    Repair = CV4stations;


end

function[Ramp] = Ramping_Up_Variations(Repair)

    fprintf('\t\t Ramp Up Variations.\n');

    % Ramp = 'Ramped_Up';
    Ramped_Up = 1;

    Ramp = Repair * Ramped_Up;

end

function[SetUp_Var1] = SetUp_Variations(Ramp)

    fprintf('\t\t Set Up Variations.\n');

    MTTS = 1;
    MTBS = 0;
    % SetUp_Var1 = 'SetUp Variation Effects';
    SetUp_Eff = MTBS /(MTTS + MTBS);
    %SetUp_Var1 = SetUp_Eff  +  Ramp
    %SetUp_Var1 = SetUp_Eff *  Ramp
    %SetUp_Var1 =  Ramp * (1/SetUp_Eff)
```

```
    SetUp_Var1 = SetUp_Eff  +  Ramp;

end

function[Qlty_Var1] = Quality_Variations(SetUp_Var1)

    fprintf('\t\t Quality Variations.\n');

    % Qlty_Var1 = 'Quality Variations Effect';
    Qlty_Eff = 1;
    Qlty_Var1 = SetUp_Var1 * Qlty_Eff;
   % Var_CRs = Qlty_Var1;
end
```

Equipment Related Disruption Sample MATLAB code

```
function [EQUIP1] = Equipment_DownTime ()
fprintf('\t\t Looking at Equipment DownTime.\n');

 fprintf('\t\t Run To Failure -------------.\n');

 fprintf('\t\t MTTF -------------.\n');
%  MTTF = 24*30*6;
 fprintf('\t\t Computation of Mean Time To Repair MTTR -------------.\n');
%  MTTI = 0.5;
%  MTTC = 0.25;
%  MTTA = 0.25;
%  MTTD = 0.25;
%  MTTL = 0.25;
%  MTTS = 0.25;
%  MTTO= MTTI + MTTC + MTTA + MTTD + MTTL + MTTS;
%  MRT = 3;
%  MTTY = 15;
%  MTTR = MTTO + MRT + MTTY;
%  Ae1 = MTTF / (MTTF + MTTR)

    mr11 = 4;  % aa followed by part# station#
    mr12 = 4;
    mr13 = 4;
    mr14 = 4;
    mf11 = 24*30*6; % 6 months in hours
    mf12 = 24*30*6;
```

```
  mf13 = 24*30*6;
  mf14 = 24*30*6;
  Ab11 = mf11/(mf11 +mr11);
  Ab12 = mf12/(mf12 +mr12);
  Ab13 = mf13/(mf13 +mr13);
  Ab14 = mf14/(mf14 +mr14);

  mr21 = 2; % in hours
  mr22 = 2;
  mr23 = 2;
  mr24 = 2;
  mf21 = 24*365; % 1 year in hours
  mf22 = 24*365;
  mf23 = 24*365;
  mf24 = 24*365;
  Ab21 = mf21/(mf21 +mr21);
  Ab22 = mf22/(mf22 +mr22);
  Ab23 = mf23/(mf23 +mr23);
  Ab24 = mf24/(mf24 +mr24);

  mr31 = 2; %  in hours
  mr32 = 2;
  mr33 = 2;
  mr34 = 2;
  mf31 = 24*30*6; % 3 months in hours
  mf32 = 24*30*6;
  mf33 = 24*30*6;
  mf34 = 24*30*6;
  Ab31 = mf31/(mf31 +mr31);
  Ab32 = mf32/(mf32 +mr32);
  Ab33 = mf33/(mf33 +mr33);
  Ab34 = mf34/(mf34 +mr34);


  Ab1 = Ab11 * Ab21 * Ab31;
  Ab2 = Ab12 * Ab22 * Ab32;
  Ab3 = Ab13 * Ab23 * Ab33;
  Ab4 = Ab14 * Ab24 * Ab34;

  AEall = Ab1 * Ab2* Ab3 * Ab4;



fprintf('\t\t Planned Maintenance (PM) -------------.\n');
DDT3 = 0;
DDT4 = 1;
if DDT3
```

```
fprintf('\t\t No impact on Ae --- Value Remains the same.\n');
%Ae2=Ae1;
Ae2 = AEall;

elseif DDT4
   fprintf('\t\t Change PM schedule.\n');
   Improv1 = 0.001; %Improvement in Availability 1%
   %Ae2 = Ae1  + Improv1;
   Ae2 = AEall  + Improv1;

   %[DE] = Equipment_Disruption ();
   [DE] = Equipment_Disruption (Ae2);
else
   fprintf('\t\t No Improvement Possible Now.\n');
   %Ae2 = Ae1;
   Ae2 = AEall;
   [DE] = Equipment_Disruption (Ae2);


end
  function [DE] = Equipment_Disruption (outputDDT)
   DED = outputDDT;
   DE1=1;
   if DE1
    fprintf('\t\t Comapre Options and do CBA.\n');
    % Insert code to do cost benefit analysis
    %DED1 = DED * 1.0000009;
    DED1 = DED * 1;
   else
      fprintf('\t\t Operations & Maintenance GoTo OM.\n');
      %[OM] = Operations_Maintenence();
      [OM] = Operations_Maintenence(DED);
   end

   DE2 = 1;
   DE3 = 0;
   if ~ DE2
      fprintf('\t\t Compare Options Again.\n');

       % Insert code to do cost benefit analysis Comparison Again
       DED2 = DED;

   elseif ~DE3
      fprintf('\t\t Operations & Maintenance GoTo OM.\n');
      DED2 = DED1;
      %[OM] = Operations_Maintenence();
      [OM] = Operations_Maintenence(DED2);
```

```
else
   fprintf('\t\t Buy and Install Machines ---- Compute the New Availability Factor.\n');

    % Insert code
    %Impr_New_Machines = 1.0001;
    Impr_New_Machines = 1;
    DED3 = DED * Impr_New_Machines;

end

 function [OM] = Operations_Maintenence(outputDED)
  OM = outputDED;
 OM1 = 1;
 OM2 = 0;
 OM3 = 0;
 OM4 = 1;
 OM5 = 1;
 if ~OM1 && OM4 && OM5
     fprintf('\t\t Look for Improvements.\n');
     OM = OM;
 elseif ~OM1 && ~OM4
     fprintf('\t\t Prepare and Implement.\n');
     fprintf('\t\t Look for Improvements.\n');
     OM = OM;
 elseif ~OM1 && OM4 && ~OM5
     fprintf('\t\t SetUp Plans and Implement.\n')
     fprintf('\t\t Look for Improvements.\n');
     OM = OM;
 elseif OM1 && ~OM2 && OM4 && ~OM5
      fprintf('\t\t Get Service from Others.\n');
      fprintf('\t\t SetUp Plans and Implement.\n');
      fprintf('\t\t Look for Improvements.\n')
      OM = OM;
 elseif  OM1 && ~OM2 && OM4 && OM5
     fprintf('\t\t Get Service from Others.\n');
     fprintf('\t\t Look for Improvements.\n');
     OM = OM;
 elseif  OM1 && ~OM2 && ~OM4
     fprintf('\t\t Get Service from Others.\n');
     fprintf('\t\t Prepare and Implement.\n');
     fprintf('\t\t Look for Improvements.\n');
     OM = OM;
 elseif OM1 && OM2 && OM3 && OM4 && OM5
      fprintf('\t\t Repair and Fix the Machines.\n');
      fprintf('\t\t Look for Improvements.\n');
      OM = OM;
 elseif OM1 && OM2 && OM3 && OM4 && ~OM5
```

```
      fprintf('\t\t Repair and Fix the Machines.\n');
      fprintf('\t\t SetUp Plans and Implement.\n');
      fprintf('\t\t Look for Improvements.\n')
      OM = OM;
   elseif OM1 && OM2 && OM3 && ~OM4 && OM5
      fprintf('\t\t Repair and Fix the Machines.\n');
      fprintf('\t\t Prepare and Implement.\n');
      fprintf('\t\t Look for Improvements.\n');
      OM = OM;
  elseif OM1 && OM2 && ~OM3 && OM4 && ~OM5
      fprintf('\t\t Put Plans to Hire Repair Person.\n')
      fprintf('\t\t SetUp Plans and Implement.\n');
      fprintf('\t\t Look for Improvements.\n')
      OM = OM;
  elseif OM1 && OM2 && ~OM3 &&~OM4
      fprintf('\t\t Put Plans to Hire Repair Person.\n')
      fprintf('\t\t Prepare and Implement.\n');
      fprintf('\t\t Look for Improvements.\n');
      OM = OM;
   elseif OM1 && OM2 && ~OM3 && OM4 && OM5
      fprintf('\t\t Put Plans to Hire Repair Person.\n')
      fprintf('\t\t Look for Improvements.\n')
      OM = OM;
   end

  OM= OM;
  end

DE4 = 0;
DE5 = 0;
if ~DE4 && ~DE5
    fprintf('\t\t Compute TC and PC.\n')
    % Insert equations for TC & PC
    fprintf('\t\t Make Improvements so that PC is in acceptable limits.\n');
    % Insert equations to compute improved Ae
    %ImprTCPC= 1.000001;
    ImprTCPC= 1;
    OM = ImprTCPC * OM;
elseif DE4 && DE5
    % Insert equations to compute improved Ae
    %Impr_OM = 1.0001;
    Impr_OM = 1;
    OM = Impr_OM * OM;
end

DE15 =0;
DE16 =0;
```

```
DE17 =0;
DE18 =0;
DE20 =1;
DE22 =0;
if ~DE15 && DE16 && DE18
   fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
   % Insert Reliability Equations
   fprintf('\t\t Make Improvements.\n')
   % Insert equations to compute improved Ae
   %Impr_RelI = 1.0005;
   Impr_RelI = 1;
   Ae3 = OM * Impr_RelI;
elseif ~DE15 && ~DE16 && ~DE17 && DE20 && DE22
    fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
    fprintf('\t\t Fix the Scheduling Issues.\n')
     % Insert equations to compute improved Ae
     %Impr_RelS = 1.0001;
      Impr_RelS = 1;
     Ae3 = OM * Impr_RelS;
elseif ~DE15 && ~DE16 && ~DE17 && DE20 && ~DE22
    fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
    fprintf('\t\t Fix the Scheduling Issues.\n')
    fprintf('\t\t Align all the Schedules.\n')
     % Insert equations to compute improved Ae
     %Impr_RelSA = 1.00001;
     Impr_RelSA = 1;
     Ae3 = OM * Impr_RelSA;
elseif  ~DE15 && DE16 && ~DE18 && DE20 && DE22
    fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
    fprintf('\t\t Fix the Scheduling Issues.\n')
    % Insert equations to compute improved Ae
    %Impr_RelS = 1.0001;
    Impr_RelS = 1;
    Ae3 = OM * Impr_RelS
elseif  ~DE15 && DE16 && ~DE18 && DE20 && ~DE22
    fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
    fprintf('\t\t Fix the Scheduling Issues.\n')
    fprintf('\t\t Align all the Schedules.\n')
    % Insert equations to compute improved Ae
    %Impr_RelSA = 1.00001;
    Impr_RelSA = 1;
    Ae3 = OM * Impr_RelSA;
elseif ~DE15 && DE16 && ~DE18 && ~DE20 && DE22
    fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
    % Insert equations to compute improved Ae
    %Impr_Rel = 1.0005;
    Impr_Rel = 1;
```

```
        Ae3 = OM * Impr_Rel;
    elseif  ~DE15 && DE16 && ~DE18 && ~DE20 && ~DE22
        fprintf('\t\t Compute Relaiability of Machines in the Critical Path.\n')
        fprintf('\t\t Align all the Schedules.\n')
        % Insert equations to compute improved Ae
        %Impr_RelA = 1.000001;
        Impr_RelA = 1;
         Ae3 = OM * Impr_RelA;
    elseif DE15 && DE16 && DE18
        fprintf('\t\t Make Improvements.\n')
        % Insert equations to compute improved Ae
        %Impr_I = 1.0000007;
        Impr_I = 1;
        Ae3 = OM * Impr_I;
    elseif DE15 && ~DE16 && ~DE17 && DE20 && DE22
        fprintf('\t\t Fix the Scheduling Issues.\n')
        % Insert equations to compute improved Ae
        %Impr_S = 1.0000007;
        Impr_S = 1;
        Ae3 = OM * Impr_S;
    elseif DE15 && ~DE16 && ~DE17 && DE20 && ~DE22
        fprintf('\t\t Fix the Scheduling Issues.\n')
        fprintf('\t\t Align all the Schedules.\n')
        % Insert equations to compute improved Ae
        %Impr_SA= 1.0000009;
        Impr_SA= 1;
        Ae3 = OM * Impr_SA;
    elseif DE15 && DE16 && ~DE18 && DE20 && ~DE22
        fprintf('\t\t Fix the Scheduling Issues.\n')
        fprintf('\t\t Align all the Schedules.\n')
        % Insert equations to compute improved Ae
        %Impr_SA= 1.0000009;
        Impr_SA= 1;
        Ae3 = OM * Impr_SA;

    end
   DE=Ae3;
   end

EQUIP1=DE


end
```

Level Batch Size Determination Sample MATLAB code

```
  function LevelBatchSizeSample()
 % developed by: Tomcy Thomas
clear all
clc
%
disp('--------------------------------');
disp('Batch Selection Algorithm');
disp('--------------------------------');

XTOT = 428;
tempcheck = 60;
X2 = 10;
X3 = 10;

BAT5=0;

while BAT5 == 0

    fprintf('\nUser options:\n');
    fprintf('\t Single piece or Batch?\n');
    prompt = {'Single Piece or Batch?'};
    dlg_title = 'BAT1';
    num_lines = 1;
    def = {'1'};
    answer = inputdlg(prompt,dlg_title,num_lines,def);
    BAT1 = str2num(answer{1});
    if BAT1==0
        fprintf('\t\t Single piece selected.\n');
    else
        fprintf('\t\t Batch selected.\n');
    end

    fprintf('\t Fixed or Random?\n');
    prompt = {'Fixed or Random?'};
    dlg_title = 'BAT2';
    num_lines = 1;
    def = {'1'};
    answer = inputdlg(prompt,dlg_title,num_lines,def);
    BAT2 = str2num(answer{1});
    if BAT2==0
        fprintf('\t\t Fixed selected.\n');
    else
        fprintf('\t\t Random selected.\n');
    end
```

```
fprintf('\t Small batchsize or Large batch size?\n');
prompt = {'Small batchsize or Large batch size?'};
dlg_title = 'BAT3';
num_lines = 1;
def = {'1'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
BAT3 = str2num(answer{1});
if BAT3==0
    fprintf('\t\t Small batchsize selected.\n');
else
    fprintf('\t\t Large batchsize selected.\n');
end

fprintf('\t Range of random batch size?\n');
prompt = {'Range of random batch size'};
dlg_title = 'BAT4';
num_lines = 1;
def = {'0'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
BAT4 = str2num(answer{1});
fprintf('\t\t %d selected for random batch size range \n',BAT4);

% outputs
fprintf('\nSystem evalutation results:\n');
output_str1 = 'Failed to Get Any Result';
if ~BAT1
    fprintf('\t Single Piece Manufacturing System 1 \n');
    output_str1 = 'Single Piece Manufacturing System 1';

elseif BAT1 && ~BAT2 && ~BAT3
    fprintf('\t Small Batchsize System \n');
    output_str1 ='Small Batchsize System';

elseif BAT1 && ~BAT2 && BAT3
    fprintf('\t Large Batchsize System \n');
    output_str1 ='Large Batchsize System';

elseif BAT1 && BAT2 && BAT3
    fprintf('\t Large Batchsize System \n');
    output_str1 ='Large Batchsize System';

elseif BAT1 && BAT2 && BAT4
    fprintf('\t Range is MidValue to Maximum \n');
    output_str1 ='Range is MidValue to Maximum';

elseif BAT1 && BAT2 && ~BAT4
```

```
    fprintf('\t Range is 1 to MidValue \n');
    output_str1 ='Range is 1 to MidValue';

else

    fprintf('\t No valid Process Selection Possible\n');
    output_str1 = 'No valid Process Selection Possible';
end

msgbox(output_str1);
DCCombo1 = zeros(X2, X3);
fprintf('\nBatch size calculations:\n');
success=0;
maxiter = 3;
niter = 0;
while success==0  && niter<maxiter;

    for tempX12 = 1:X2;
        for tempXC = 1:X3;
            if tempcheck>= (XTOT/tempXC)/tempX12;
                DCCombo1(tempX12,tempXC)=1;
                success=1;
            else
                DCCombo1(tempX12,tempXC)=0;
            end;
        end;
    end;
    if success==0;
        warndlg('Failed to get the results');
    end;
    niter = niter +1;
end;
if niter==maxiter
    fprintf('\t Did not find any of the combinations of X2 and X3 possible . Quitting.\n');
    warndlg('Did not find any of the combinations of X2 and X3 possible . Quitting.');
    return;
end;

save('DCCombo1.mat','DCCombo1', 'X2', 'X3');
fprintf('\t Saving DCCombo1 output file... ');
filename = 'DCCombo1.xlsx';
xlswrite(filename, DCCombo1, 1);
fprintf('done.\n');
fprintf('\t Please review %s. Do you accept batch size selection?\n',filename);
prompt = {'Do you Accept Batchsize Selection?'};
dlg_title = 'BAT5';
num_lines = 1;
```

```
    def = {'1'};
    answer = inputdlg(prompt,dlg_title,num_lines,def);
    BAT5 = str2num(answer{1});

    if BAT5
        fprintf('\t\t Batch size selection accepted!\n');
        output_str2 = 'Batchsize Selection Accepted';
    else ~BAT5;
        fprintf('\t\t Batch size selection rejected. Please repeat process.\n');
        output_str2 = 'Rejected Batchsize Selection - Repeat Batchsize Selection';
    end
    msgbox(output_str2);
end;

Yin = 1500;
T1 = 17;
T2 = 14;
T3 = 45;
T4 = 25;
X14 = 300;
X7 = XTOT;

BAT6=0;

while BAT6 == 0
    fprintf('\nTime to finish (TF) calculations:''\n');

    TflowIssues = -1*ones(X2*X3, 7);
    index =1;

    for B = 1:X2
        for R = 1:X3
            if R == 1
                TFF1=  ( R*T1*B) + T2 + T3 +  ( ((ceil(Yin))/(R*X14))*T4) ;
            else
                TFF1=  ( R*T1*B) + T2 + T3 +  ceil(((Yin/R)/(X14/T4))) +  ((R*R)/B);
            end;

            X1j = ceil(X7/(R*B));
            X8 = X1j*R*B;
            CTT = ceil(TFF1);

            try
                TTCombo = [ B R TFF1 CTT DCCombo1(B,R) X1j X8];
            catch

                fprintf('Error in creating TTCombo row at index %d .\n',index);
```

```
        end;
        TflowIssues(index,:) = TTCombo;
        index = index + 1;
      end;
    end;

    save('TflowIssues.mat', 'TflowIssues','X2', 'X3', 'TFF1','CTT', 'DCCombo1', 'X1j','X8');
    fprintf('\t Saved DCCTComboV2 output file.\n');
    load TflowIssues;

    fprintf('\t Saving TflowIssues output file... ');
    TFmatrix = 'TflowIssues.xlsx';
    xlswrite(TFmatrix, TflowIssues, 1);
    fprintf('done.\n');

    fprintf('\t Please review %s output file. Do you accept TF?\n', TFmatrix);
    prompt = {'Accept TF??'};
    dlg_title = 'BAT6';
    num_lines = 1;
    def = {'1'};
    answer = inputdlg(prompt,dlg_title,num_lines,def);
    BAT6 = str2num(answer{1});

    if BAT6
      fprintf('\t\t TF Accepted!\n');
      output_str3 = 'TF Accepted';
    else ~BAT6;
      fprintf('\t\t TF Rejected - Repeat TF calculations');
      output_str3 = 'Rejected - Repeat TF calculations';
    end;
    msgbox(output_str3);
end;
 TimeAvailable = 300;
compare1 = TflowIssues(:,4)<TimeAvailable & TflowIssues(:,5)==1 & TflowIssues(:,6)< tempcheck;
TFandTA = TflowIssues(compare1, :);
save ('ComparedResults.mat', 'TFandTA');
fprintf('\t Saving comparison output file... ');
TFandTAmatrix = 'TFandTAmatrix.xlsx';
xlswrite(TFandTAmatrix, TFandTA, 1);
fprintf('done.\n');

 output_str4 = 'Computed TF compared with TA and the feasible combinations Selected';
 msgbox(output_str4);

 fprintf('\nBatch size algorithm completed.\n');
 fprintf('\n Please review the feasible combinations Selected \n');
 msgbox('Please review the feasible combinations Selected');
```

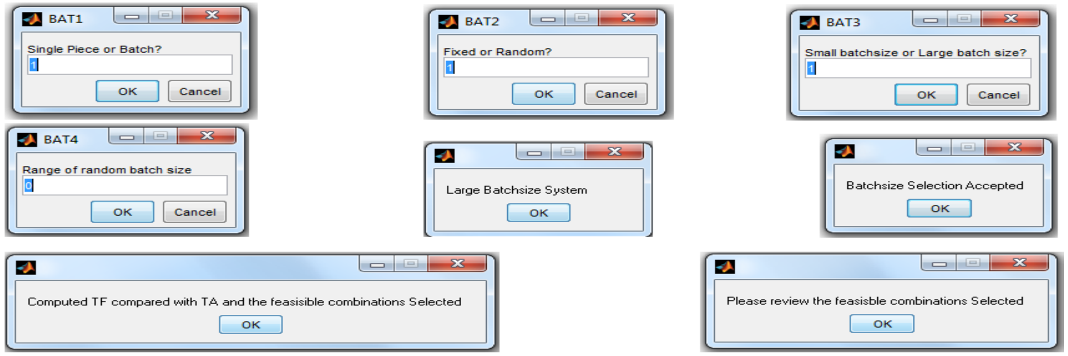


Figure C.1 Graphical User Interface Sample

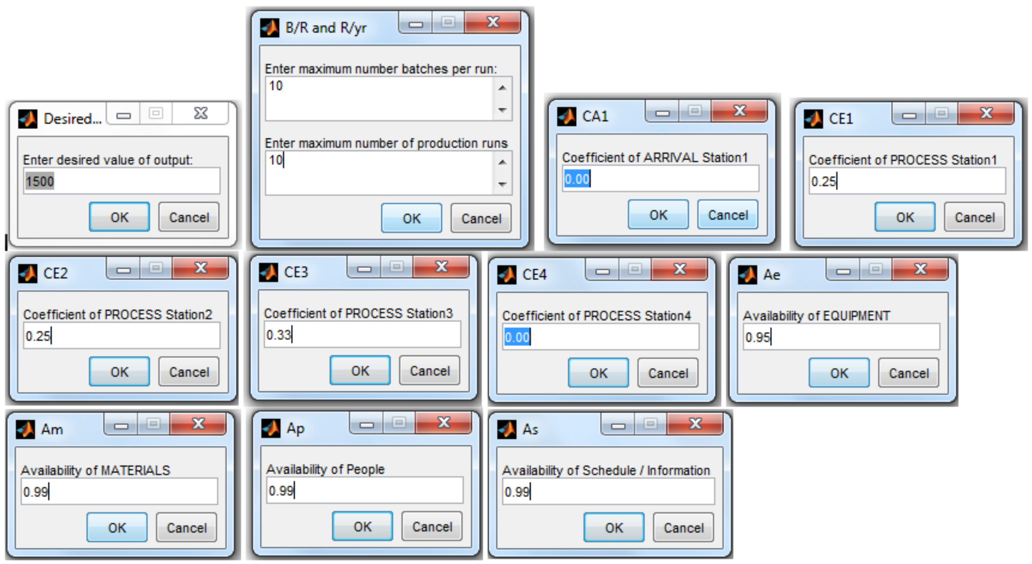


Figure C.2 GUI Screenshots

Code to generate GUI of Figure C.2

```
prompt = {'Enter desired value of output:'};
dlg_title = 'Desired Output';
num_lines = 1;
def = {'1500'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
% To store the value of the input use the command 'Variable Name' = str2num(answer{1});

prompt3 = {'Enter maximum number batches per run:','Enter maximum number of production runs' };
title3 = 'B/R and R/yr';
num_lines3 = 2;
def3 = {'10','10'};
select3 = inputdlg(prompt3,title3,num_lines3, def3);
X2 = str2num(select3{1});
X3 = str2num(select3{2});

prompt = {'Coefficient of ARRIVAL Station1'};
dlg_title = 'CA1';
num_lines = 1;
def = {'0.00'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
CA1 = str2num(answer{1});

prompt = {'Coefficient of PROCESS Station1'};
dlg_title = 'CE1';
num_lines = 1;
def = {'0.00'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
CE1 = str2num(answer{1});

prompt = {'Coefficient of PROCESS Station2'};
dlg_title = 'CE2';
num_lines = 1;
def = {'0.00'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
CE2 = str2num(answer{1});

prompt = {'Coefficient of PROCESS Station3'};
```

```
dlg_title = 'CE3';
num_lines = 1;
def = {'0.00'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
CE3 = str2num(answer{1});

prompt = {'Coefficient of PROCESS Station4'};
dlg_title = 'CE4';
num_lines = 1;
def = {'0.00'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
CE4 = str2num(answer{1});


prompt = {'Availability of EQUIPMENT'};
dlg_title = 'Ae';
num_lines = 1;
def = {'1'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
Ae = str2num(answer{1});

prompt = {'Availability of MATERIALS'};
dlg_title = 'Am';
num_lines = 1;
def = {'1'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
Am = str2num(answer{1});


prompt = {'Availability of People'};
dlg_title = 'Ap';
num_lines = 1;
def = {'1'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
Ap = str2num(answer{1});

prompt = {'Availability of Schedule / Information'};
dlg_title = 'As';
num_lines = 1;
def = {'1'};
answer = inputdlg(prompt,dlg_title,num_lines,def);
As = str2num(answer{1});
```

Appendix D

Additional Literature Review – Reverse Engineering

“Reverse engineering is the process of analyzing an object or existing system to identify its components and their interrelationships [85]. It investigates ways to redesign or produce a copy without access to the original design [85]. The final product initializes the processes with the aim of discovering how it works. The design analysis of the system components and their interrelationships within the higher level system is reverse engineering; one goal of reverse engineering is to increase manufacturability [86]. Reverse engineering refers to the method of creating engineering design and documentation data from existing parts and their assemblies; in the fields of mechanical engineering and industrial manufacturing [87]”.

The authors in [88] designed and manufactured a new product (Fire Protection Suit) by making improvements on a part by searching for a replacement and doing extensive testing. Performance was improved when compared to the old product because of the improvement and by providing an additional layer of protection. A virtual prototype of an Automotive Magnetorheological Semi-Active Differential was developed by 3D digitizing. Assembly procedure was established to create a physical prototype. The physical prototype was validated by testing [89]. In [90] the data from an existing part was captured by using a Coordinate Measuring Machine (CMM) which was changed to electronic data. Improvement was made to the part by redesigning it using special software. A prototype was developed based on the new design. A Reverse Engineering Method for DMU Maturity Management was developed by [91]. An existing tractor wheel cover was captured by 3D laser scanning and analyzed. A clay model was developed based on the captured data .and improvements were made on the original design of the product [92].

For a reverse engineering course, assignments were given to students to study products. The products were opened up and studies conducted, and the malfunction was investigated. Conceptual improvement was suggested on the products [93]. Two types of motorcycle chains were studied for their structural and rigidity properties using the appropriate tools. A new type of chain was proposed based on the result from the comparison [94]. Most of the virtual models rebuilt using current approaches in RE consider only a geometric point of view. A knowledge-based engineering (KBE) approach adapted to RE issues was proposed to provide a complete and full CAD model, including design intents [95]. Data was obtained from three damaged parts by digitization; the purpose of this was to reproduce or make a new design for some recoveries. The data was used to develop CAD models to recover and reconstruct the parts by considering parametric and geometric continuity. A CAM model was developed, and the parts were manufactured [96]. Data collected by CMM was preprocessed by software and then converted to 3D models by reconstructing features. The part (drawbar) was redesigned and 3D printed [97]. An integrated system to model complex shapes (such as automobile valve body) was used to reverse engineer that part. Prototype was developed based on the optimized model and tested [98]. The updated model of an automotive part was designed by studying about an existing part that is new; the new model at the same time keeps a strong bound with its predecessor. A prototype which was better in shape was developed and tested [99].

Appropriate hardness in the axle-hubs of cars was assured by reengineering the manufacturing process design. Material-processing system was analyzed to correct the heat-treatment process parameters; this analysis led to the new manufacturing design of the part [100]. In [101], an open manufacturing control with agile reconfiguring of resource services was studied. A new collaborative and integrated mold design practice is described in [102] by studying the current practice of mold fabrication in industry; since the product (mold) lifecycle is getting shortened, the sequence of process execution has to be reengineered to improve its efficiency [102]. Telecommunication product manufacturing enterprise has been studied from the two viewpoints of process reforming and process reengineering. Asynchronous development mode and common building blocks strategy are used for process reforming. Process reengineering was realized by establishing a high-end process graph and process interface framework [103].

The flexibility to adapt to the development of innovative products in rapidly evolving industries is very essential to success and hence new product development is one of the most critical cross functional processes. A conceptual framework that facilitates innovation, flexibility, and an understanding of the reengineering of this product planning process was proposed. The framework facilitates better planning, formation, and organization of cross-functional work teams and groups that are involved in the product development process [104].

Process reengineering was applied in medical field also. An example is a study conducted about the processes of preparing the medicines for patients in a hospital. As a result of this study, a new methodology of modeling the interactions with the hospital information system was developed and applied which reduced the medication errors and costs [105].

VITA

Tomcy Thomas graduated with a Bachelor of Engineering (Electronics) in 1991, MBA (Operations Management) in 2000; both from India. He worked in different positions from 1991 before immigrating to Canada and then to the USA. He graduated with a MS (Engineering Management) in 2010. His published papers can be found at [106], [81], [82] and [83]. There is an additional presentation [73] in a conference.